

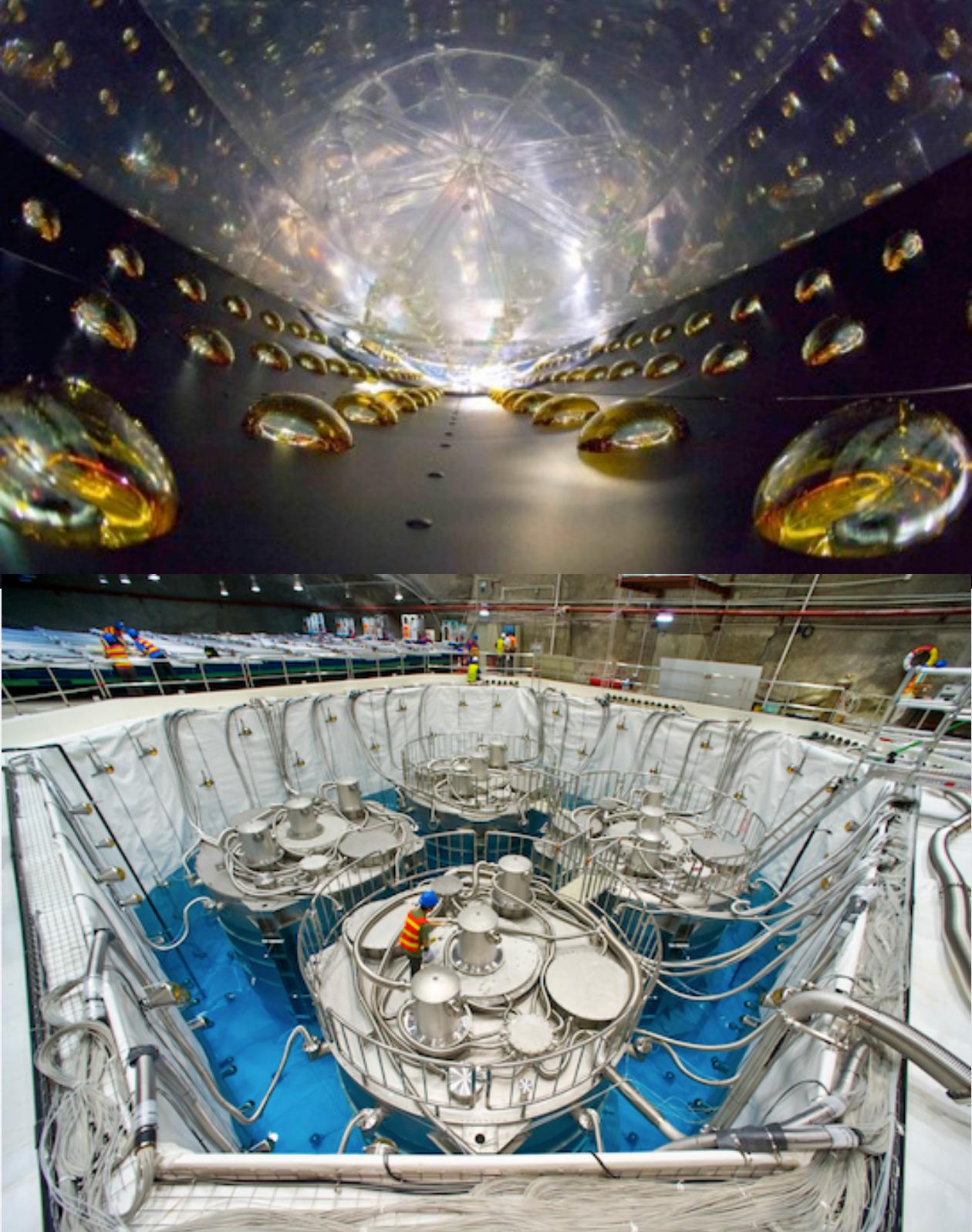
Latest Results from Daya Bay Experiment

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on behalf of the Daya Bay collaboration

INFO 13 workshop
August 25-30, 2013

Outline

- Introduction
- Daya Bay experiment
- Current data sets
- Spectrum analysis
 - Challenges and improvements
 - Oscillation parameter extraction
- Summary



Neutrino Oscillation

- Neutrino flavor (weak) eigenstates and mass eigenstates are mixed

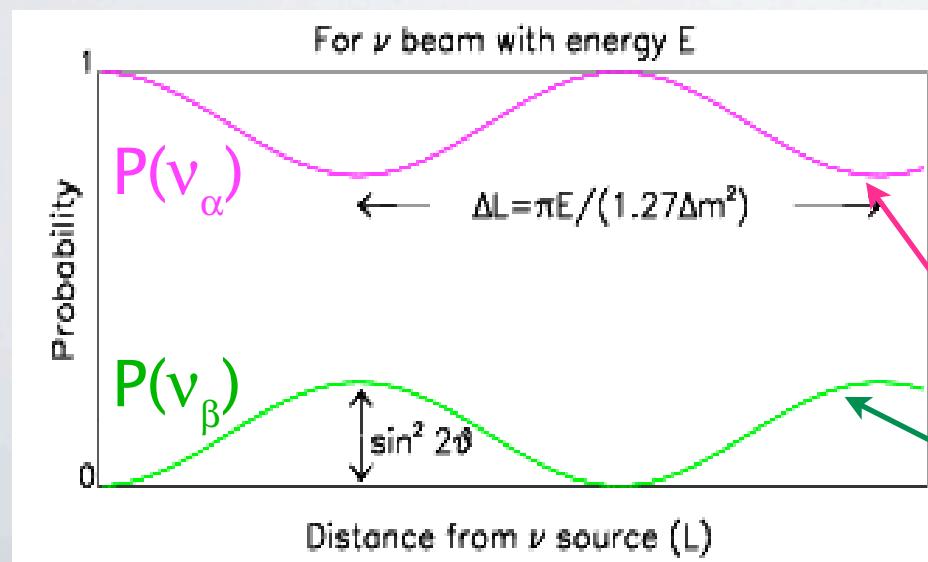
Weak eigenstate $|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$ Mass eigenstate
 $(\alpha = e, \mu, \tau)$ $i = 1, 2, 3$

MNS mixing matrix

- Neutrinos change their flavor as they travel (neutrino oscillation)
- Natural interferometer to explore fundamental nature of neutrinos

Two neutrino case:

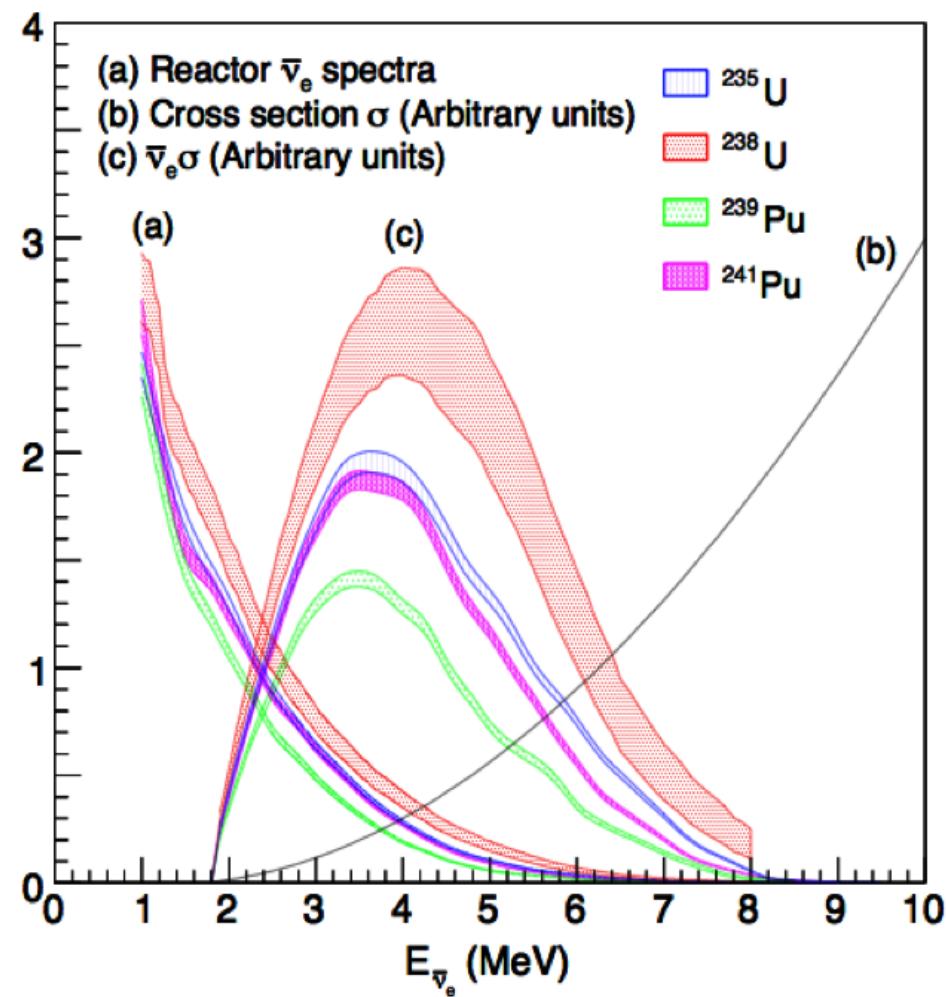
$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu(t) \rangle|^2 = \sin^2 2\theta \sin^2 \left(\Delta m^2 \frac{L}{4E} \right)$$



θ : mixing angle
 Δm^2 : mass squared difference
L : the distance traveled
E : the energy of neutrino

disappearance of ν_α
appearance of ν_β

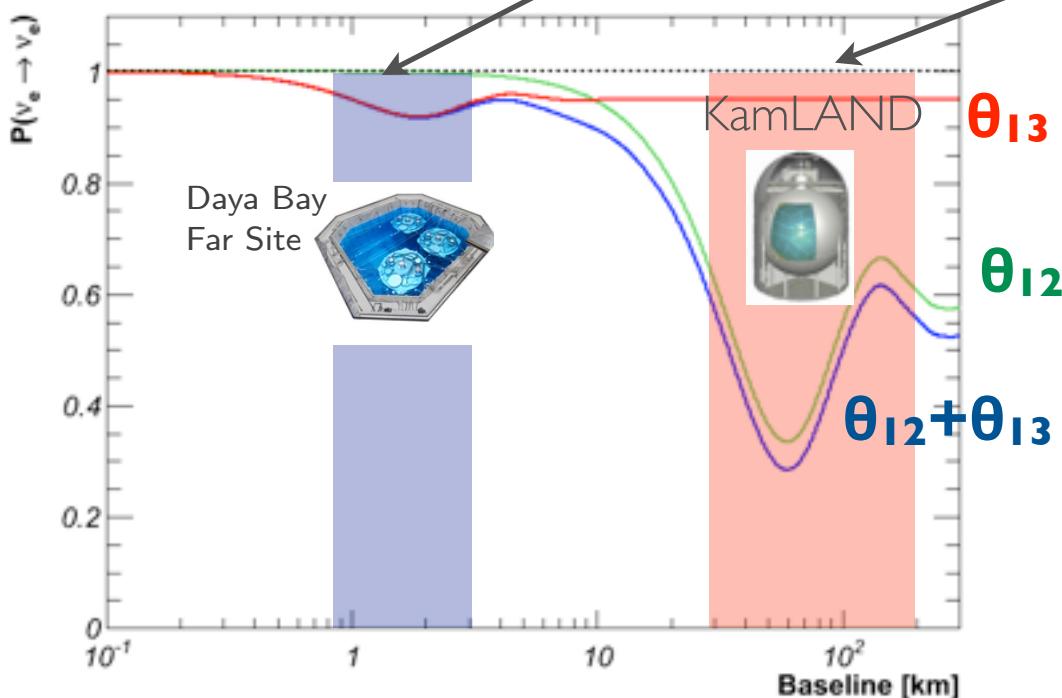
Reactor Antineutrinos



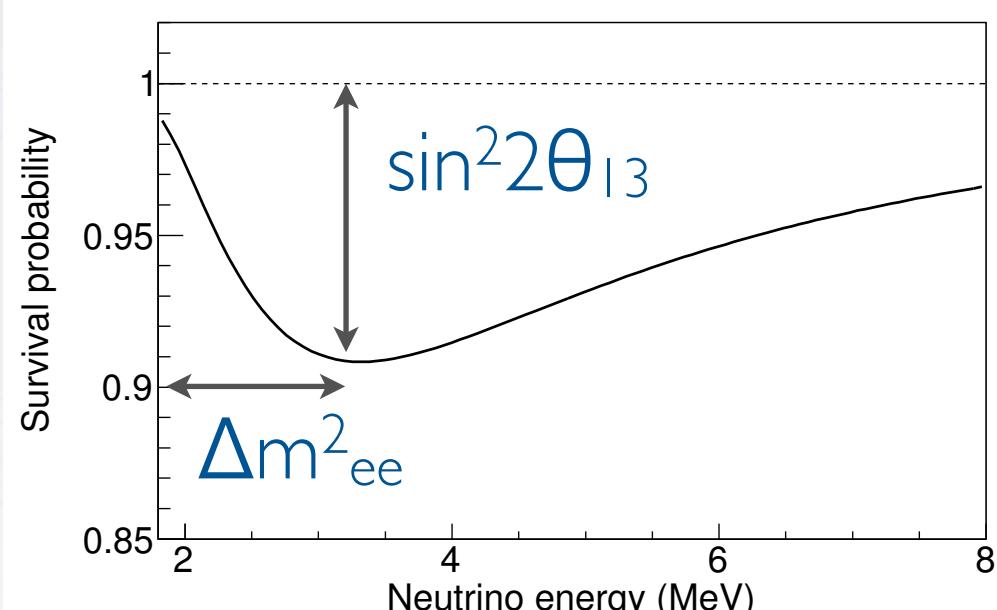
- Most powerful man-made source of antineutrinos, and it's free
- Nuclear fission release:
 - 6 antineutrinos/fission
 - Typically $\sim 10^{20}$ fissions/second
- Detected through inverse beta decay
- Broad spectrum with mean energy of ~ 4 MeV

Reactor Neutrino Oscillation

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \left(\Delta m_{ee}^2 \frac{L}{4E} \right) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2 \left(\Delta m_{21}^2 \frac{L}{4E} \right)$$



Survival probability at 1.6 km



Characteristic deficit at ~ 2 km due to θ_{13} and Δm_{ee}^2

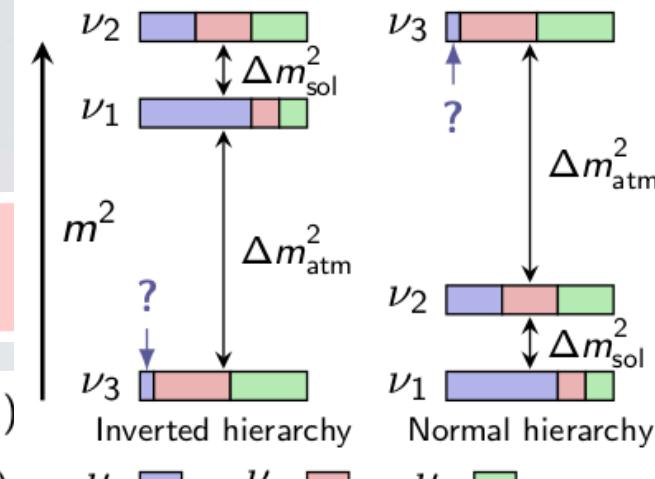
First established by Daya Bay (2012)

Now moving towards precision measurement!

Δm^2_{ee} ?

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \left(\Delta m^2_{ee} \frac{L}{4E} \right) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2 \left(\Delta m^2_{21} \frac{L}{4E} \right)$$

L $\sin^2(\Delta m^2_{ee} \frac{L}{4E}) \equiv \cos^2 \theta_{12} \sin^2(\Delta m^2_{31} \frac{L}{4E}) + \sin^2 \theta_{12} \sin^2(\Delta m^2_{32} \frac{L}{4E})$



- Oscillation at $\sim 2\text{km}$ governed by two mass splittings: Δm^2_{31} and Δm^2_{32}
- Insensitive to distinguish the two. → Effective mass splitting: Δm^2_{ee}

Can relate to actual splittings:

$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.2 \times 10^{-5} \text{ eV}^2$$

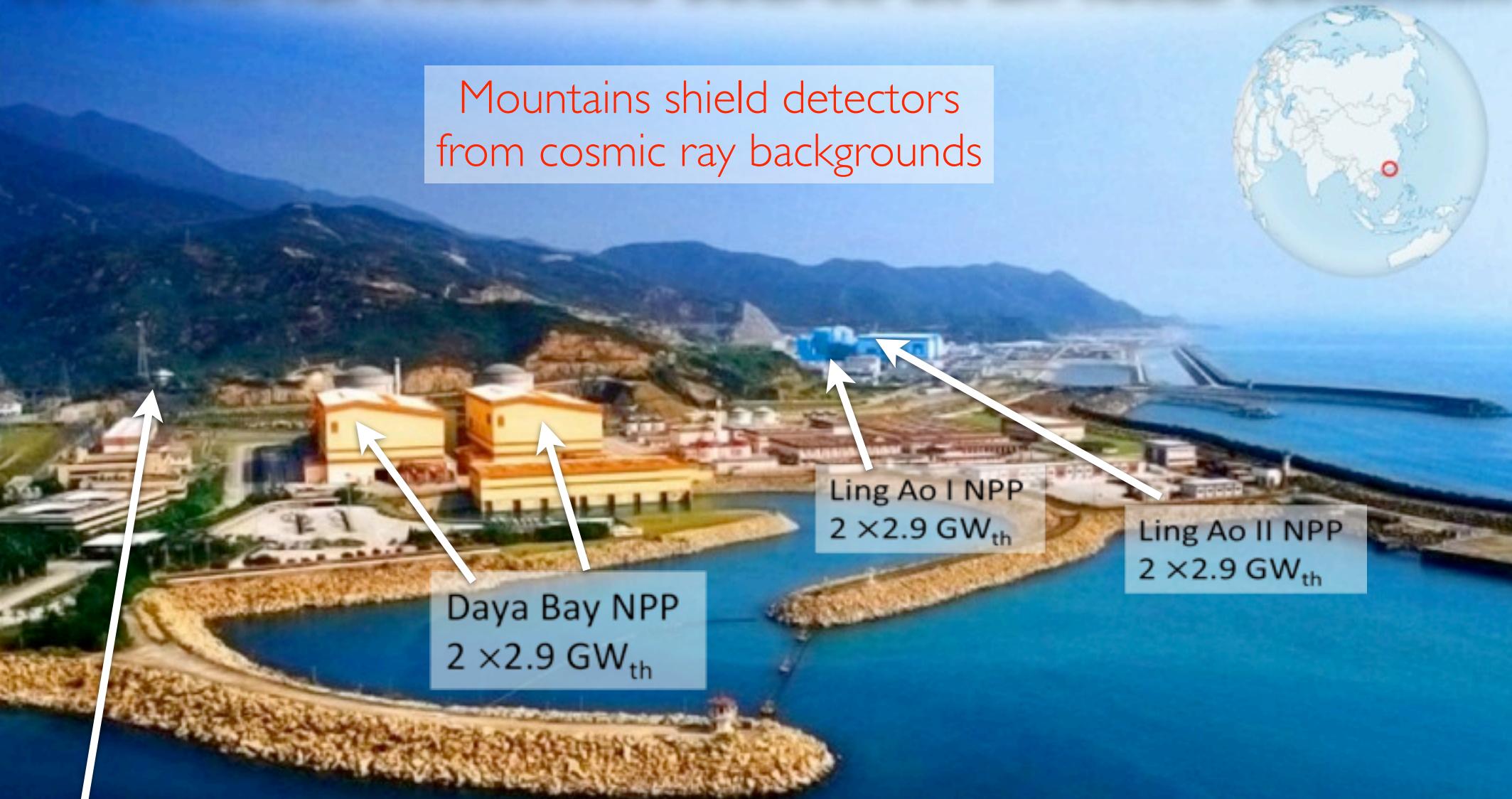
+: Normal Hierarchy
 -: Inverted Hierarchy

- Value of Δm^2_{ee} constrained by a similar quantity $\Delta m^2_{\mu\mu}$ measured by muon neutrino disappearance measurements.
- Reactor neutrinos can make independent measurement of Δm^2_{ee}
 - Important test of the oscillation model
 - Sensitive to the mass hierarchy if $\sim 1\%$ precision achieved for both Δm^2_{ee} and $\Delta m^2_{\mu\mu}$

Daya Bay Experiment



Daya Bay: A Powerful Neutrino Source at an Ideal Location

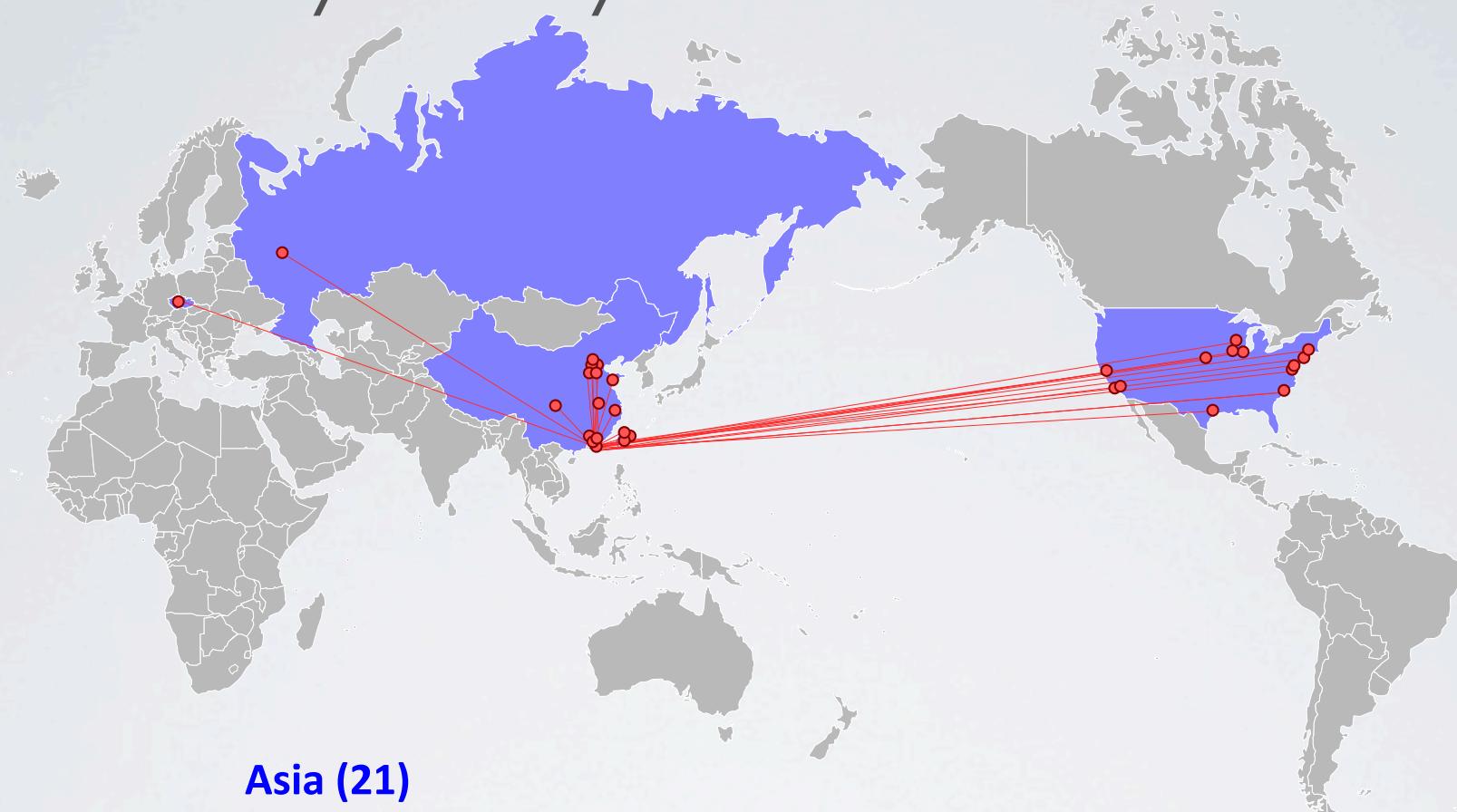


Entrance to Daya Bay
experiment tunnels

Among the top 5 most powerful reactor complexes in the world,
6 cores produce $17.4 \text{ GW}_{\text{th}}$ power, 35×10^{20} neutrinos per second



Daya Bay Collaboration



Asia (21)

Beijing Normal Univ., CGNPG, CIAE, Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

North America (17)

Brookhaven Natl Lab, CalTech, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Rensselaer Polytechnic, Siena College, UC Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

Europe (2)

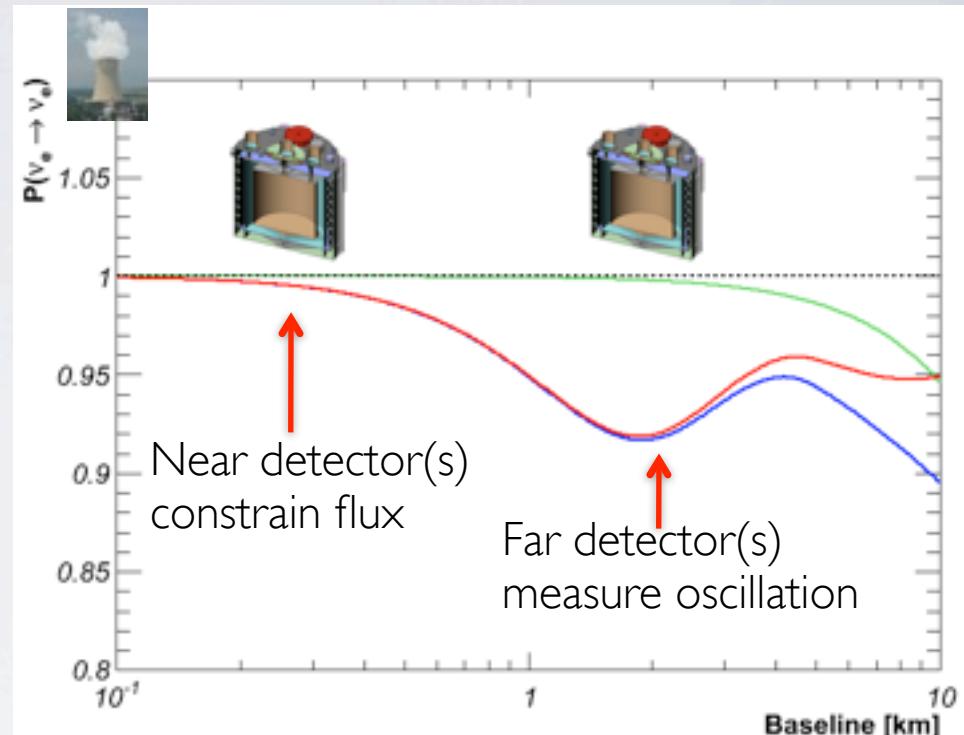
Charles University, JINR Dubna

~230 collaborators from 40 institutions

Strategy for Precise Measurement

**Relative measurement
with functionally
identical detectors**

Most of uncertainty
from detector response
and absolute flux cancel



Far/Near ν_e Ratio

Distances from
reactor

Oscillation deficit

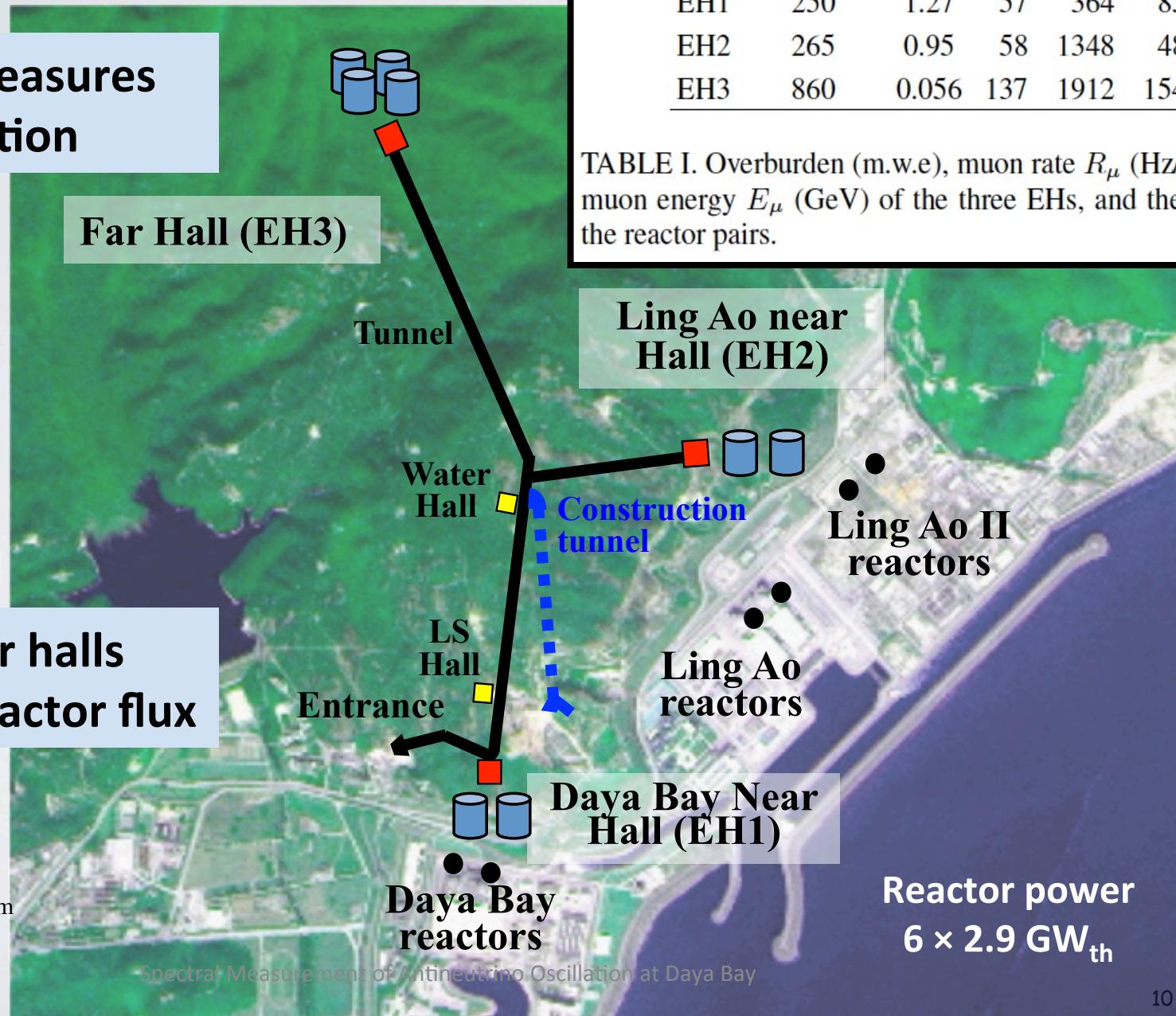
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}} \right) \left(\frac{L_n}{L_f} \right)^2 \left(\frac{\epsilon_f}{\epsilon_n} \right) \left[\frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)} \right]$$

Detector Target Mass

Detector efficiency

Experiment Layout

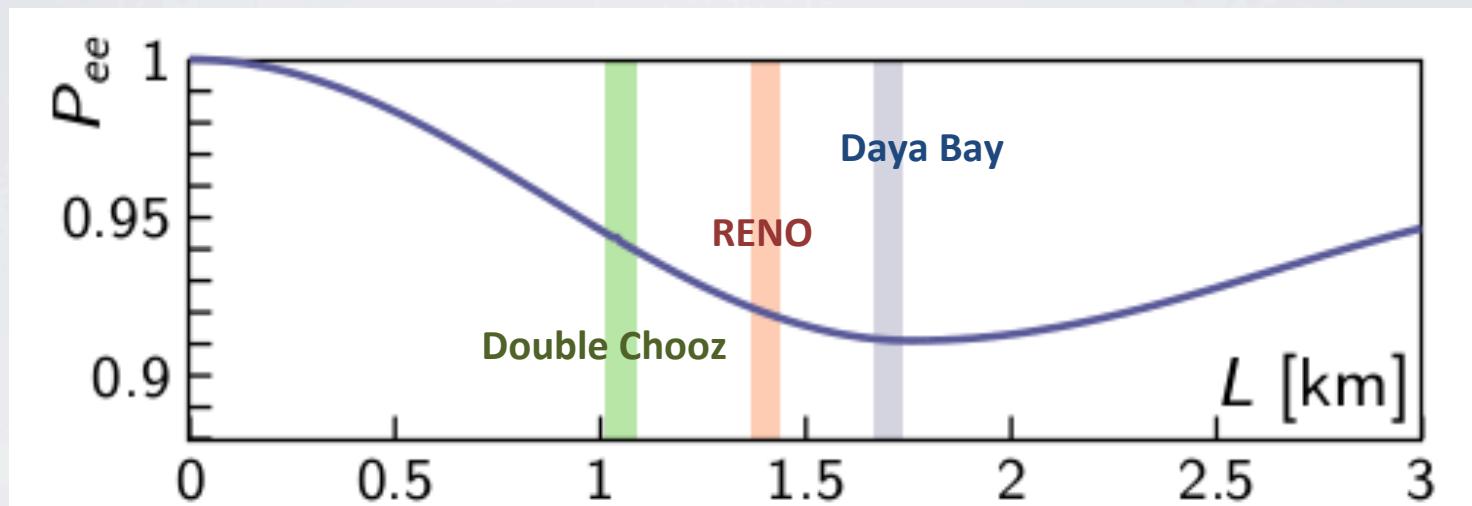
Far hall measures
oscillation



Daya Bay Advantages

Ideal baseline

- Detector locations optimized to known parameter space of Δm^2_{ee}
- Better sensitivity to both Θ_{13} and Δm^2_{ee}



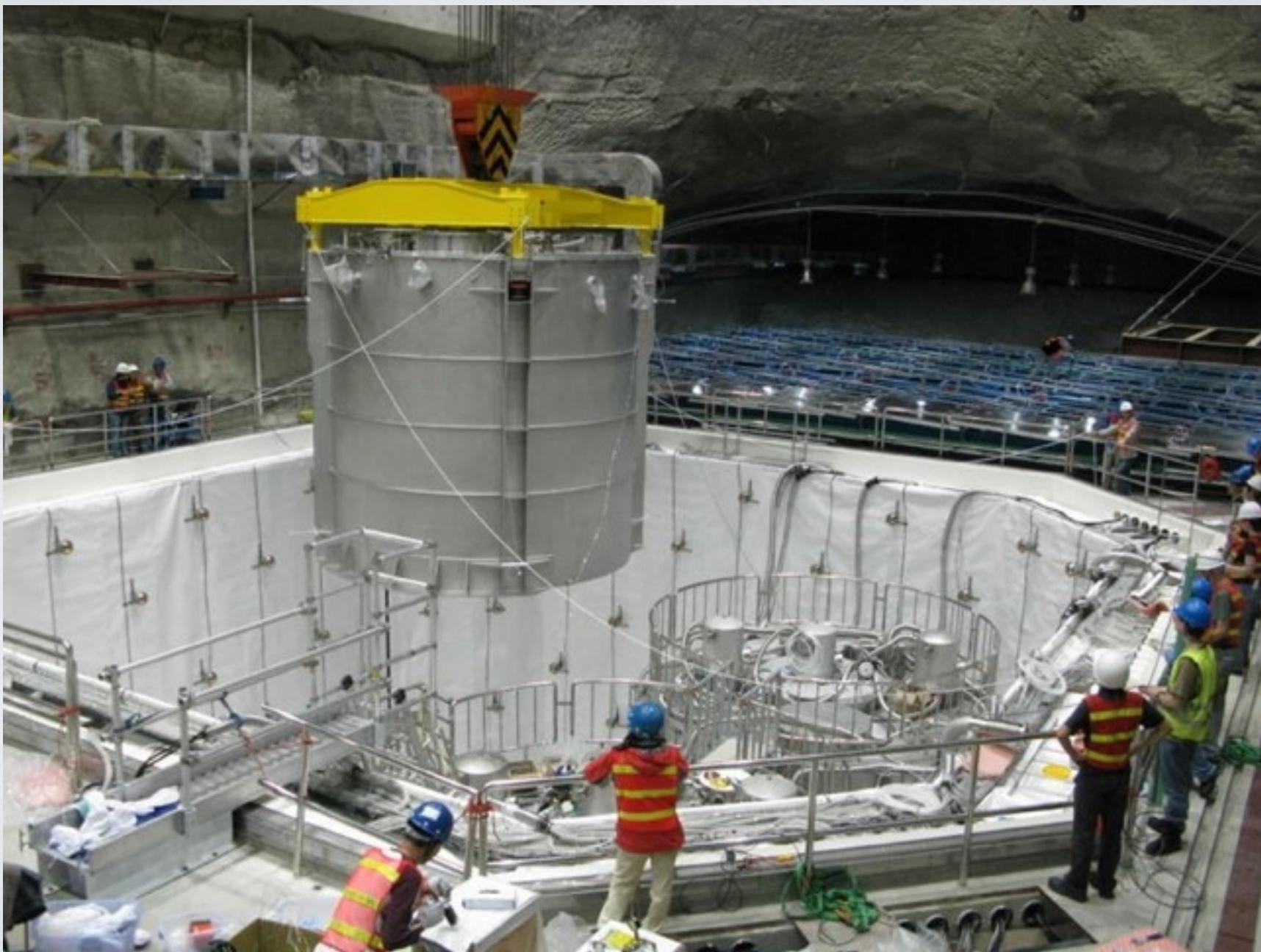
Stronger, bigger, and deeper

	Reactor [GW _{th}]	Target [tons]	Depth [m.w.e]
Double Chooz	8.6	16 (2×8)	300, 120 (far, near)
RENO	16.5	32 (2×16)	450, 120
Daya Bay	17.4	160 (8×20)	860, 250

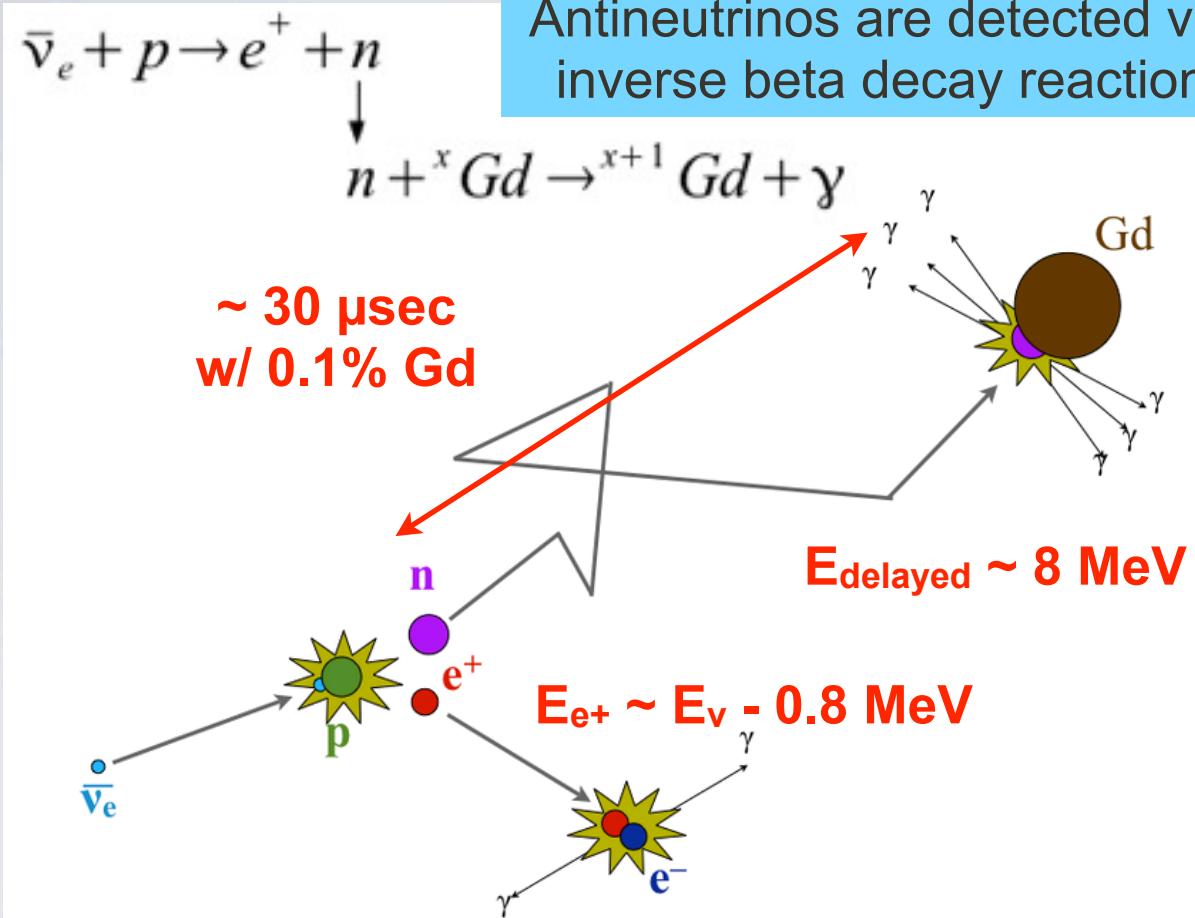
Large Signal

Low Background

Daya Bay Detector

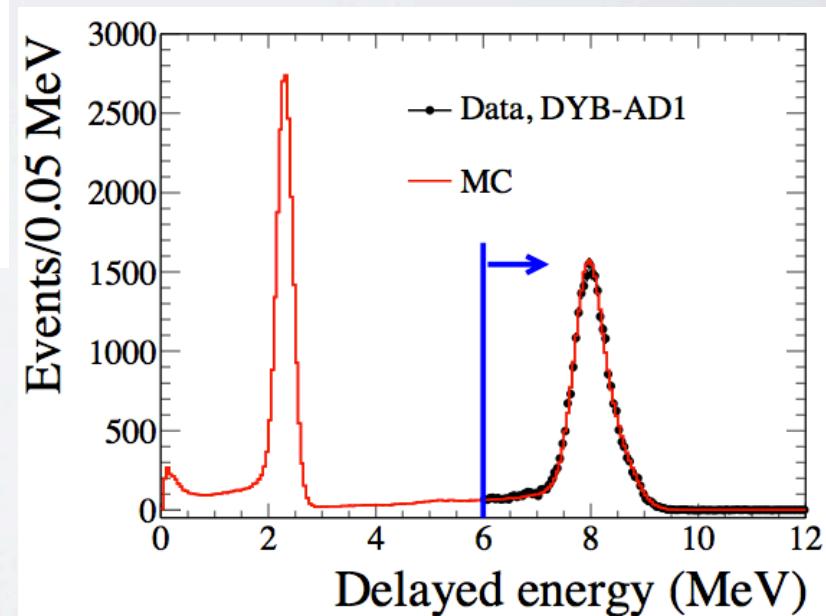
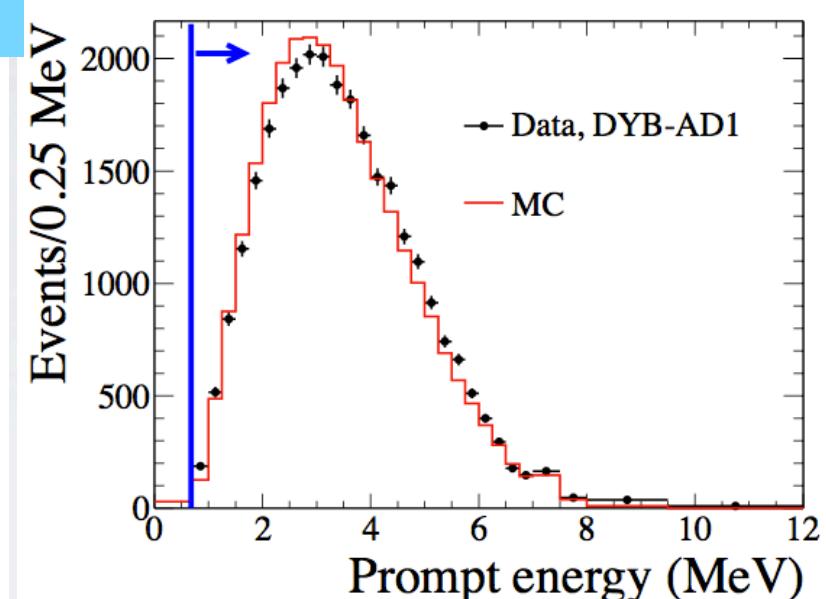


Detection Method



Prompt + Delayed coincidence

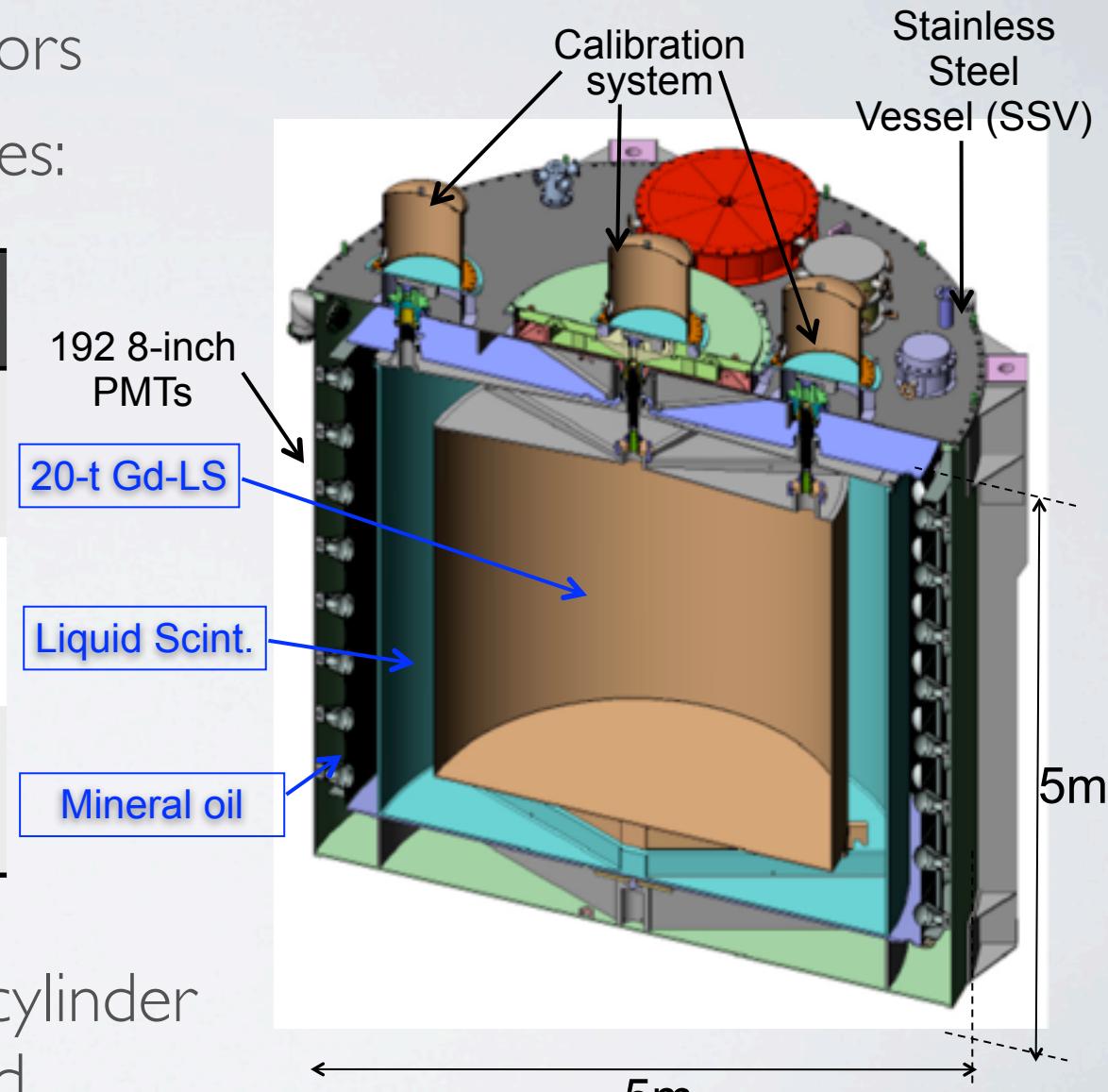
- Prompt positron: carries antineutrino energy
- Delayed neutron capture: efficiently tag antineutrino signal



Antineutrino Detector

- 8 functionally identical detectors
- Three-zone cylindrical modules:

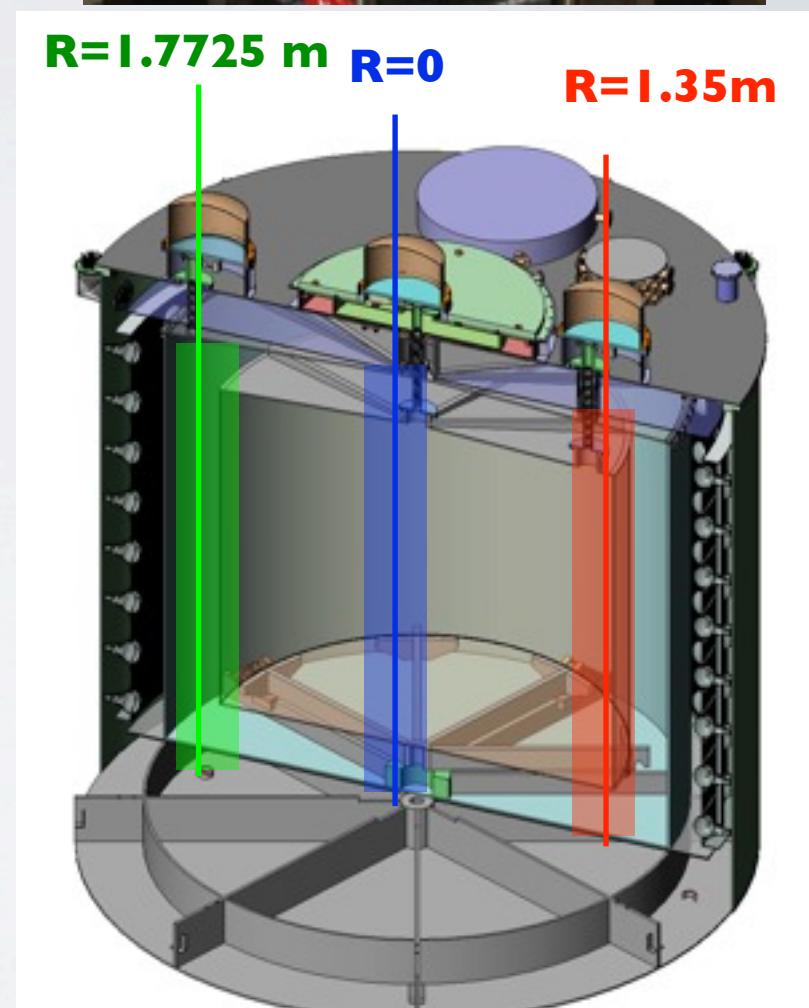
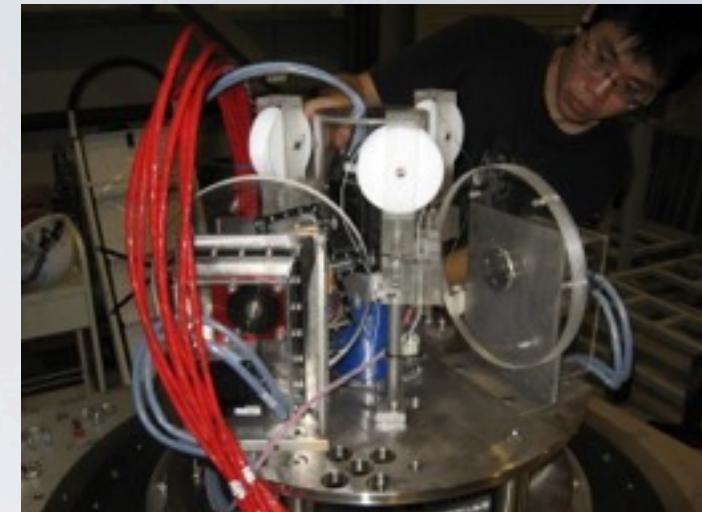
Zone	Mass	Liquid	Purpose
Inner acrylic vessel	20 t	Gd-doped liquid scintillator	Anti-neutrino target
Outer acrylic vessel	22 t	Liquid scintillator	Gamma catcher (from target zone)
Stainless steel vessel	40 t	Mineral Oil	Radiation shielding



- Reflectors at top/bottom of cylinder are used to increase light yield.

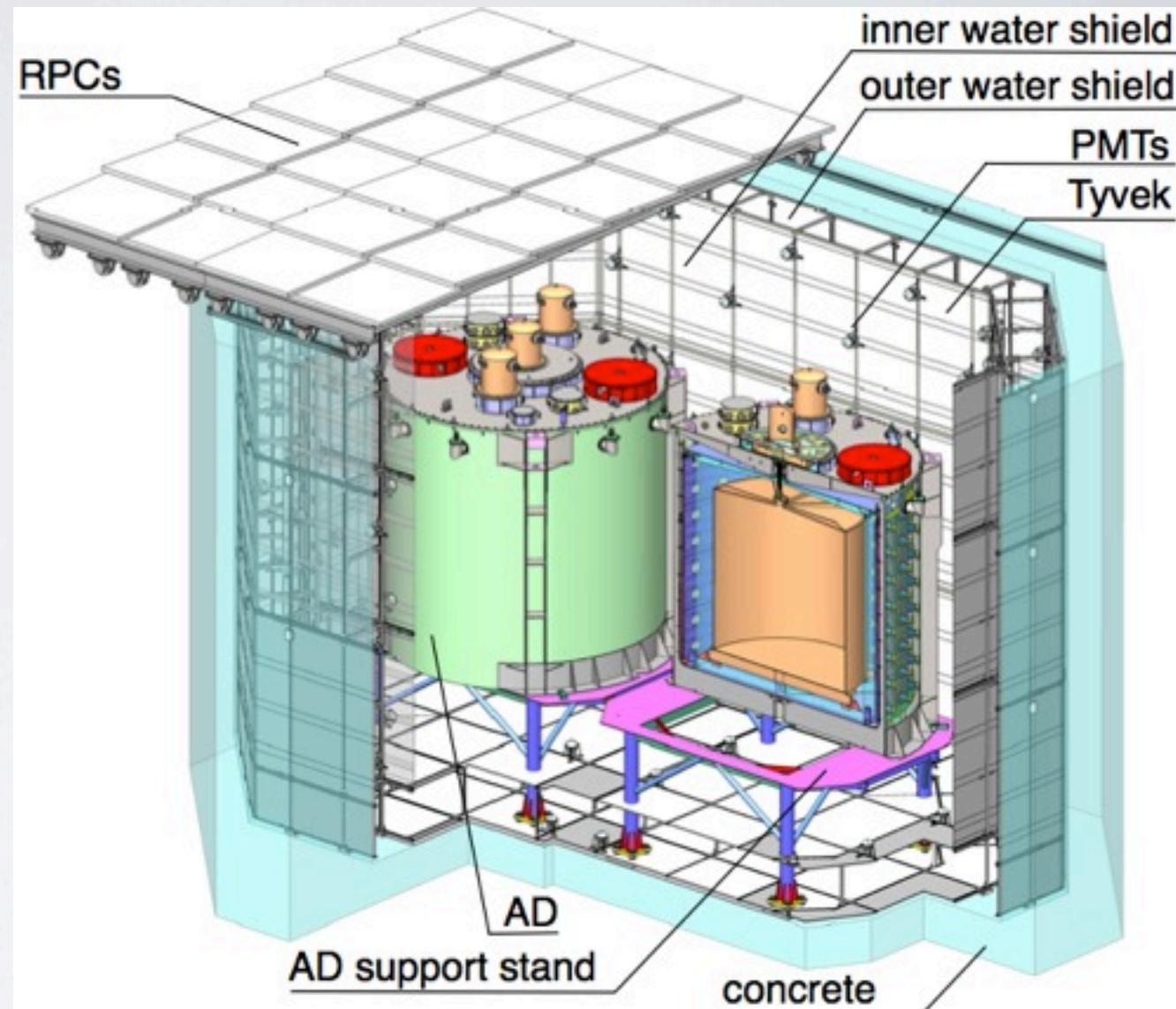
Calibration System

- Three Automated Calibration Units (ACUs) per detector.
- Deploy sources along the z-axis
- Three sources + LED in each ACU, on a turn table.
 - ^{68}Ge (γ , $2 \times 0.511 \text{ MeV}$)
 - ^{60}Co (γ , 2.506 MeV)
 - $^{241}\text{Am}-^{13}\text{C}$ (n , 8MeV)
 - LED for timing and gain calibration
- Temporary special calibration sources:
 - γ : ^{137}Cs (0.622 MeV), ^{54}Mn (0.835 MeV), ^{40}K (1.461 MeV)
 - n : $^{241}\text{Am}-^9\text{Be}$, $^{239}\text{Pu}-^{13}\text{C}$



Muon Tagging System

- 2.5 meter thick two-section water shield
 - Cherenkov detector to tag cosmic ray muons.
 - Shield for neutrons and gammas from surrounding materials.
- RPC
 - Covers water pool to provide further muon tagging.



Data Set

Data sets

Two detector comparison [1202.6181]

- 90 days of data, Daya Bay near only
- NIM A **685** (2012), 78-97

First oscillation analysis [1203.1669]

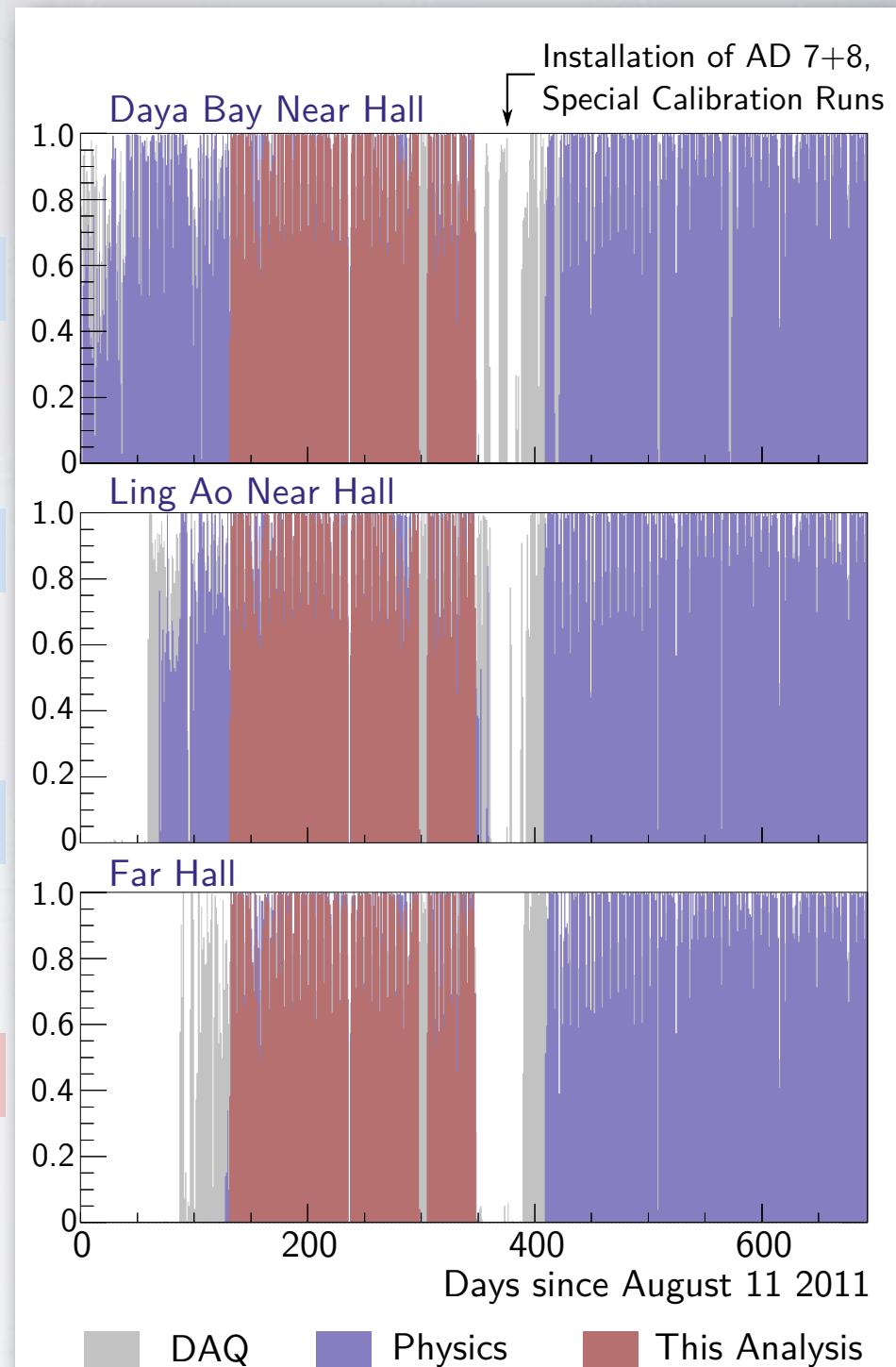
- 55 days of data, 6 ADs near+far
- PRL **108** (2012), 171803

Improved oscillation analysis [1210.6327]

- 139 days of data, 6 ADs near+far
- CP C **37** (2013), 011001

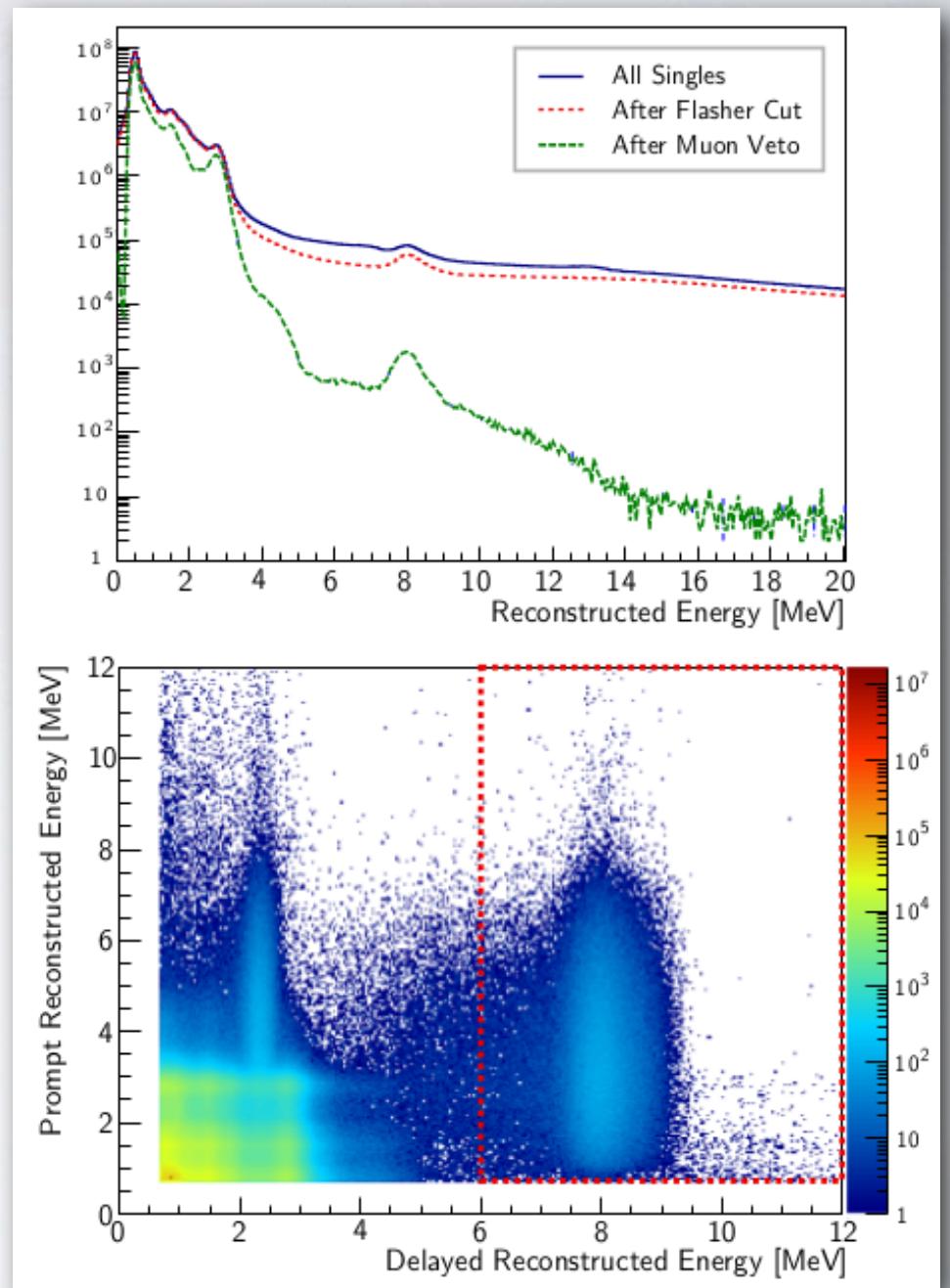
Spectral Analysis

- 217 days, complete 6 AD period
- 55% more statistics than CPC result



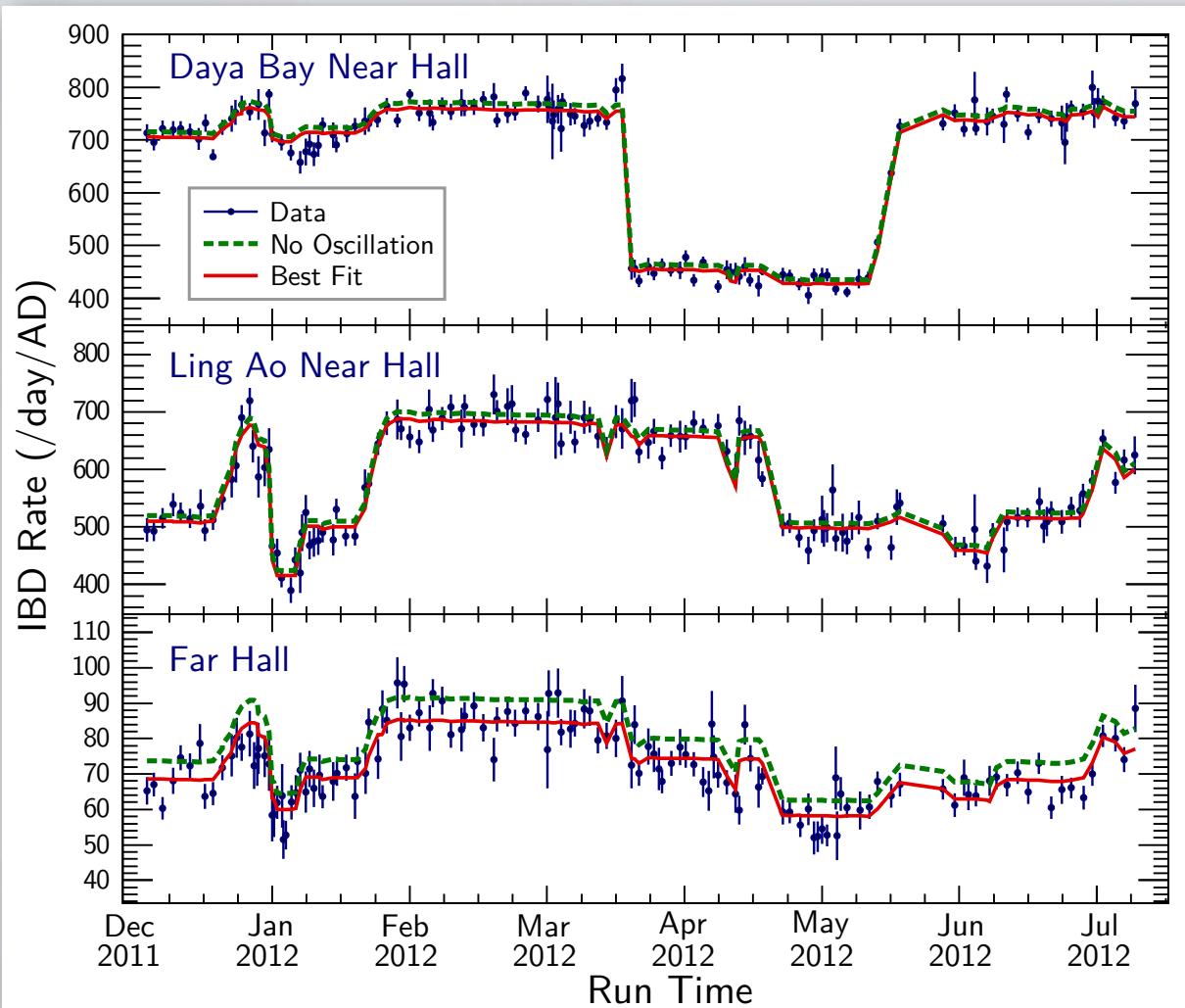
Antineutrino Selection

- ① Reject spontaneous PMT light emission ("flashers")
- ② Prompt positron:
 $0.7 \text{ MeV} < E_p < 12 \text{ MeV}$
- ③ Delayed neutron:
 $6.0 \text{ MeV} < E_d < 12 \text{ MeV}$
- ④ Neutron capture time:
 $1 \mu\text{s} < t < 200 \mu\text{s}$
- ⑤ Muon veto:
 - Water pool muon (>12 hit PMTs):
Reject $[-2\mu\text{s}; 600\mu\text{s}]$
 - AD muon (>3000 photoelectrons):
Reject $[-2 \mu\text{s}; 1400\mu\text{s}]$
 - AD shower muon ($>3 \times 10^5$ p.e.):
Reject $[-2 \mu\text{s}; 0.4\text{s}]$
- ⑥ Multiplicity:
 - No additional prompt-like signal
 $400\mu\text{s}$ before delayed neutron
 - No additional delayed-like signal
 $200\mu\text{s}$ after delayed neutron



Antineutrino Rate vs. Time

Detected rate strongly correlated with reactor flux expectations



- Predicted rate assumes no oscillation
- Absolute normalization determined by fit to data
- Normalization within a few percent of expectations

Signal and Background Summary

	Near Halls				Far Hall	
	AD1	AD2	AD3	AD4	AD5	AD6
IBD candidates	101290	102519	92912	13964	13894	13731
DAQ live time (day)	191.001		189.645		189.779	
Efficiency	0.7957	0.7927	0.8282	0.9577	0.9568	0.9566
Accidentals (/day/AD)*	9.54±0.03	9.36±0.03	7.44±0.02	2.96±0.01	2.92±0.01	2.87±0.01
Fast neutron (/day/AD)*	0.92±0.46		0.62±0.31		0.04±0.02	
$^8\text{He}/^9\text{Li}$ (/day/AD)*	2.40±0.86		1.20±0.63		0.22±0.06	
Am-C corr. (/day/AD)*			0.26±0.12			
$^{13}\text{C}(\alpha, n)^{16}\text{O}$ (/day/AD)*	0.08±0.04	0.07±0.04	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02
IBD rate (/day/AD)*	653.30 ± 2.31	664.15 ± 2.33	581.97 ± 2.07	73.31 ± 0.66	73.03 ± 0.66	72.20 ± 0.66

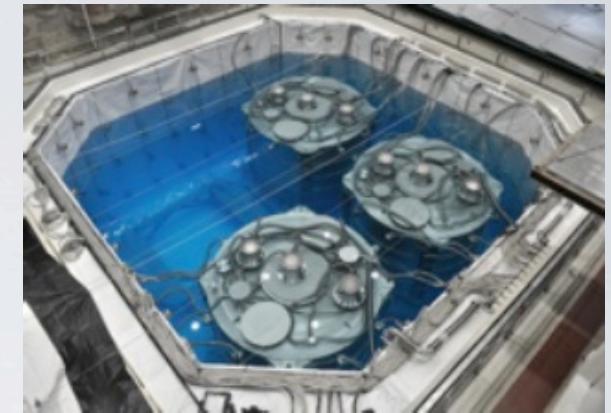
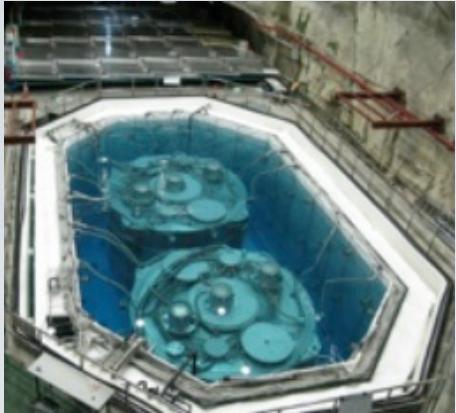
* Corrected for the efficiency of the muon veto and multiplicity cuts

Collected more than 300k antineutrino interactions

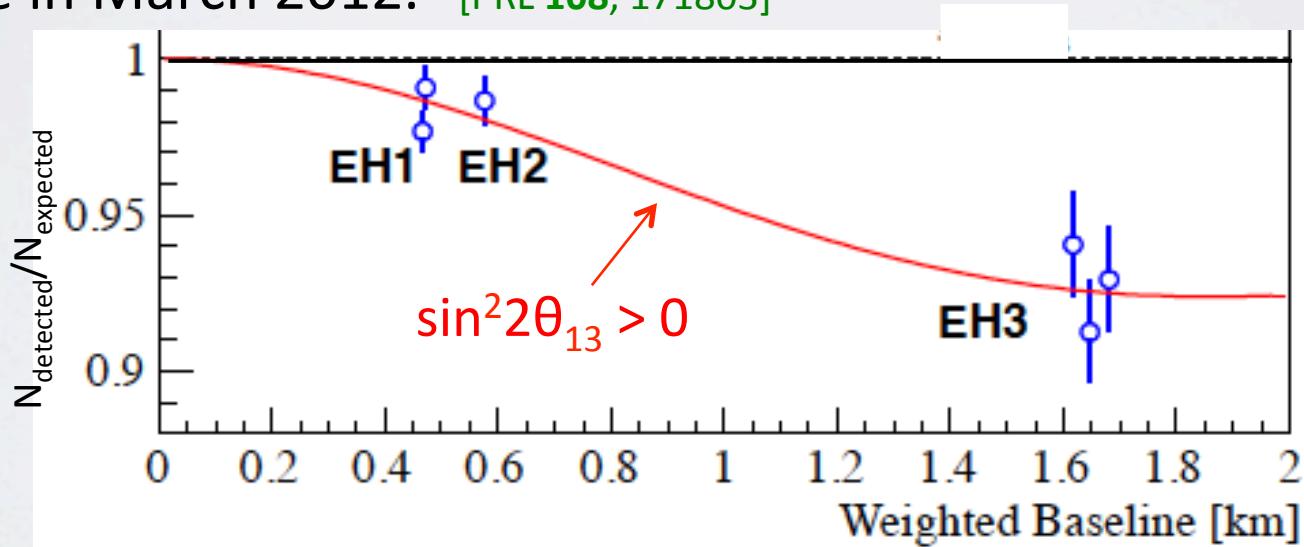
- Consistent rates for side-by-side detectors
- Uncertainties still dominated by statistics

Oscillation Analysis

Initial results



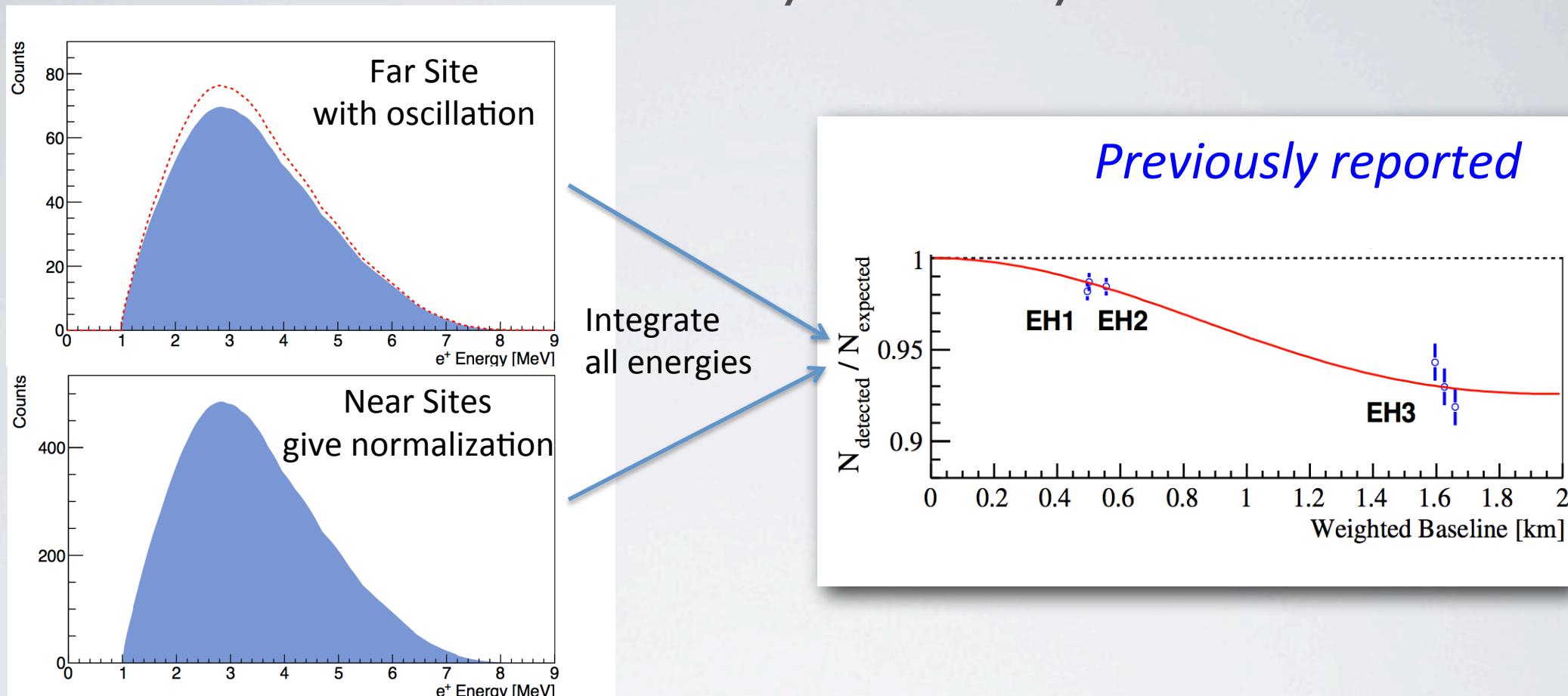
Based on 55 days of data with 6 ADs, discovered disappearance of reactor $\bar{\nu}_e$ at short baseline in March 2012. [PRL 108, 171803]



Obtained the most precise value of θ_{13} in Jun. 2012:

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005 \quad [\text{CPC 37, 011001}]$$

Rate Only Analysis

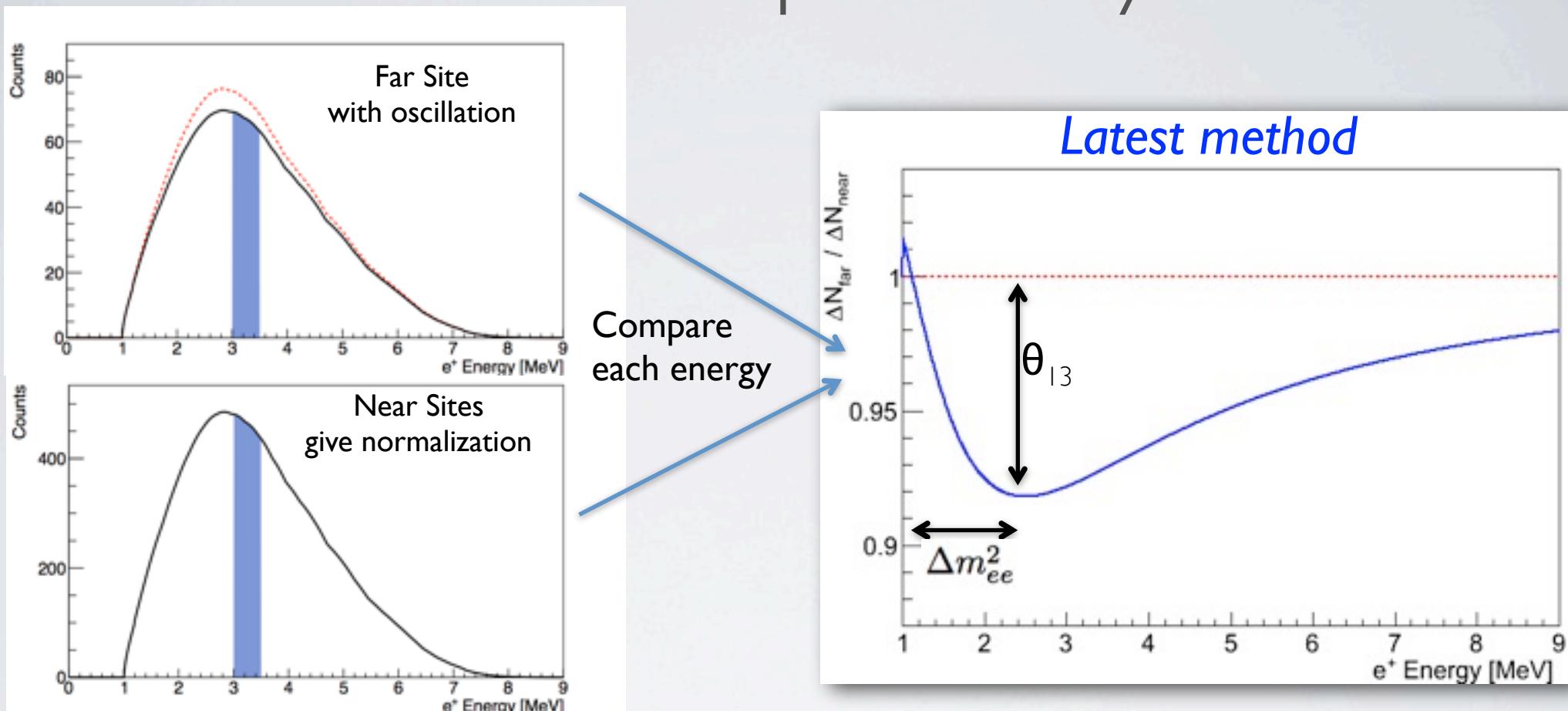


$$\frac{N_{\text{far}}}{N_{\text{near}}} = \frac{N_{\text{protons,far}}}{N_{\text{protons,near}}} \frac{1/L_{\text{far}}^2}{1/L_{\text{near}}^2} \frac{\epsilon_{\text{far}}}{\epsilon_{\text{near}}} \frac{\int_{E_{\min}}^{E_{\max}} P_{ee}(E, L_{\text{far}}; \theta_{13}, \Delta m_{ee}^2) \sigma(E) \Phi(E) dE}{\int_{E_{\min}}^{E_{\max}} P_{ee}(E, L_{\text{near}}; \theta_{13}, \Delta m_{ee}^2) \sigma(E) \Phi(E) dE}$$

Advantage: Fewer systematic uncertainties

Disadvantages: Less sensitive. Unable to constrain Δm_{ee}^2

Rate + Shape Analysis



$$\frac{\frac{dN_{\text{far}}}{dE}}{\frac{dN_{\text{near}}}{dE}} = \frac{N_{\text{protons,far}}}{N_{\text{protons,near}}} \frac{1/L_{\text{far}}^2}{1/L_{\text{near}}^2} \frac{\epsilon_{\text{far}}}{\epsilon_{\text{near}}} \frac{P_{ee}(E, L_{\text{far}}; \theta_{13}, \Delta m_{ee}^2) \sigma(E) \Phi(E)}{P_{ee}(E, L_{\text{near}}; \theta_{13}, \Delta m_{ee}^2) \sigma(E) \Phi(E)}$$

Advantages: Gain sensitivity from energy dependence. Constrain Δm_{ee}^2 .

Disadvantages: Require detailed understanding of detector response

Challenges for the spectrum shape analysis

- Understanding of background rate and shape
- Understanding of the detector response
 - Energy resolution
 - Energy scale
 - Effect of inactive volume (acrylic vessel)

Challenges for the spectrum shape analysis

- **Understanding Background rate and shape**
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Understanding Background Rate and Shape

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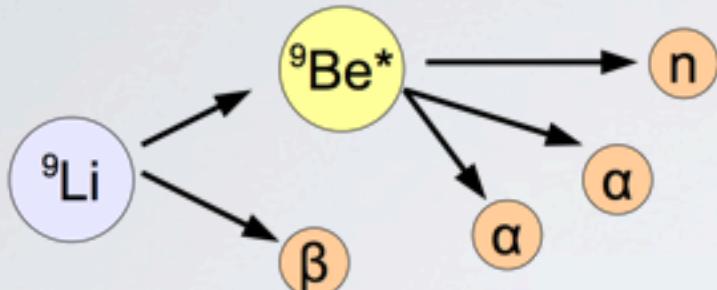
Two worst contributors to background uncertainty at the far hall

${}^8\text{He}/{}^9\text{Li}$ Backgrounds

DIRECTORY measured by fitting
the distribution of IBD
candidates vs. time since muon

β -n decay:

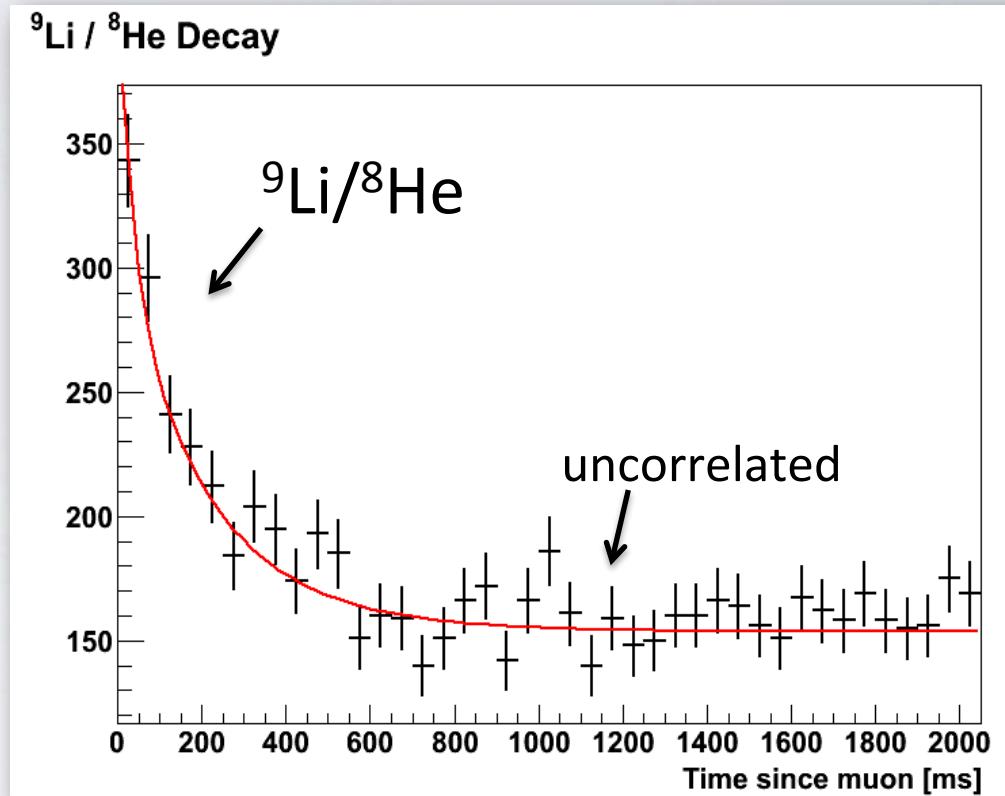
- Prompt: β -decay
- Delayed: neutron capture



${}^9\text{Li}$: $\tau_{1/2} = 178$ ms, $Q = 13.6$ MeV

${}^8\text{He}$: $\tau_{1/2} = 119$ ms, $Q = 10.6$ MeV

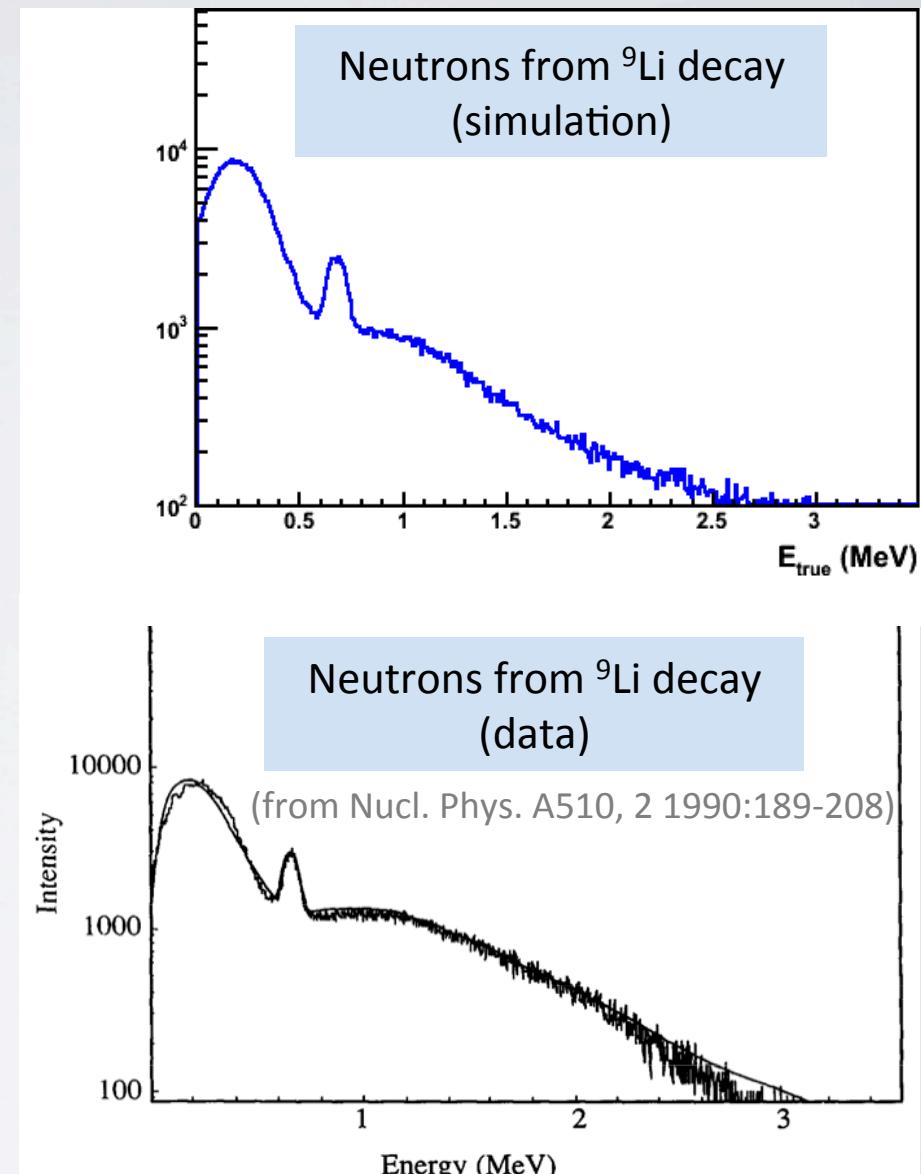
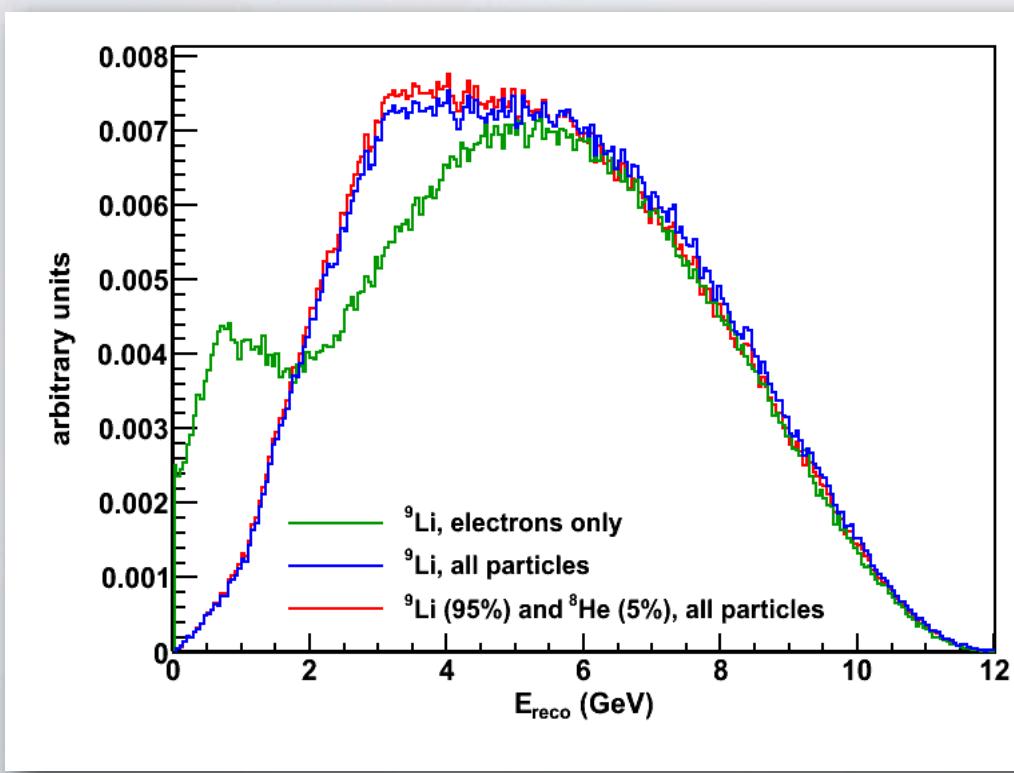
- Generated by cosmic rays
- Long-lived
- Mimic antineutrino signal



**Analysis muon veto cuts
control B/S to $\sim 0.3 \pm 0.1\%$**

${}^8\text{He}/{}^9\text{Li}$ Backgrounds

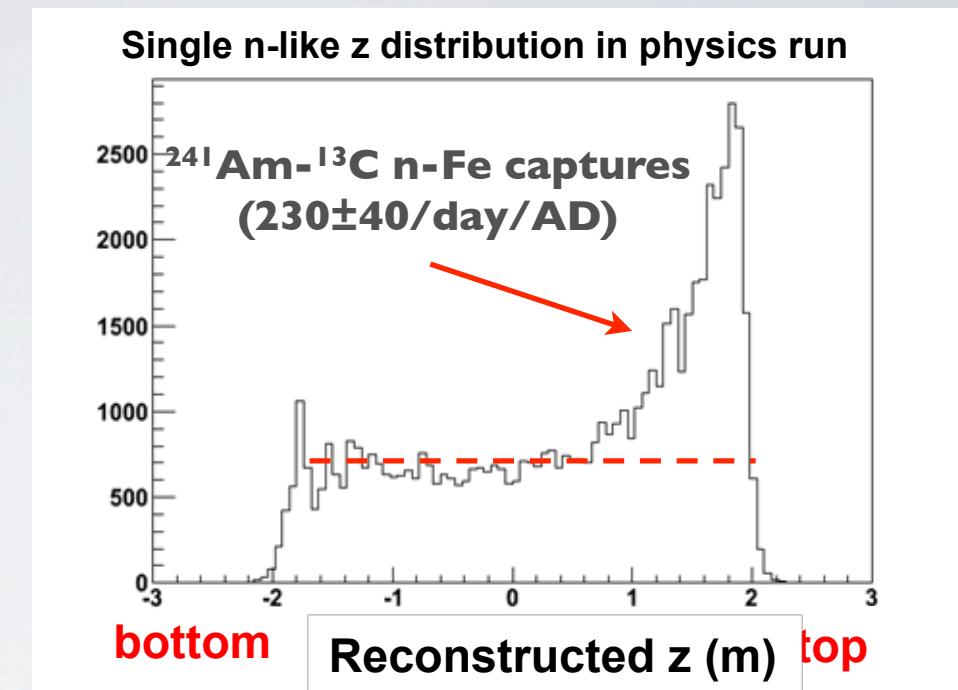
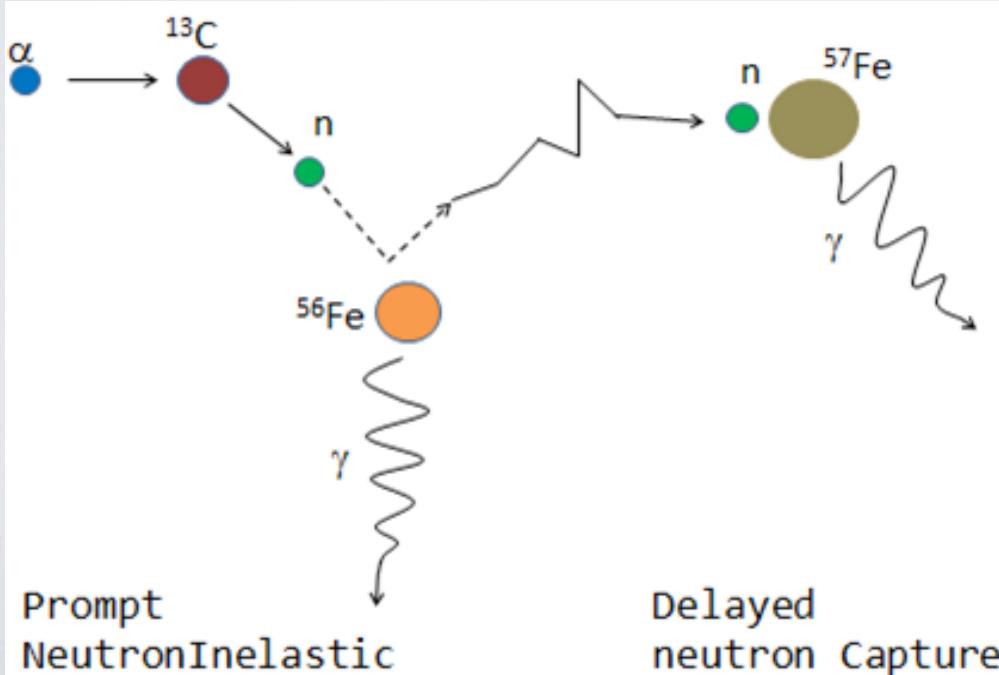
- Simulated ${}^8\text{He}/{}^9\text{Li}$ spectra including neutron and alpha contributions
- Benchmarked with external data
- Uncertainty in shape is conservatively estimated by varying ${}^9\text{Li}/({}^9\text{Li}+{}^8\text{He})$ ratio and detector response model



^{241}Am - ^{13}C Background

Subtle background from our calibration source

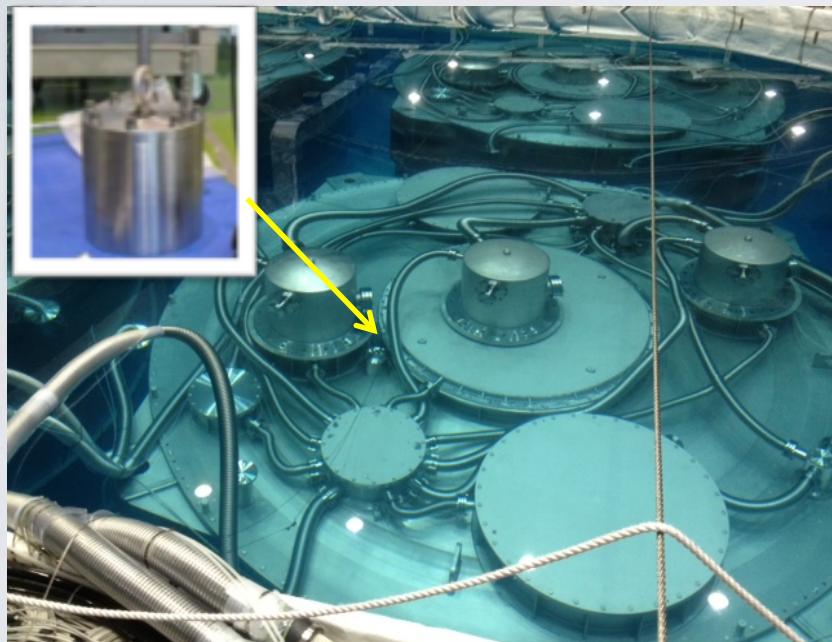
- ^{241}Am - ^{13}C source produces ~ 0.75 Hz neutron via $^{13}\text{C}(\alpha, n)^{16}\text{O}$
- Neutron interact with steel to produce fake prompt-delayed pair



- Background rate expected to be small: 0.2-0.3/day/module (MC)
- Yet, one of the largest source of systematic uncertainty from backgrounds

^{241}Am - ^{13}C Background

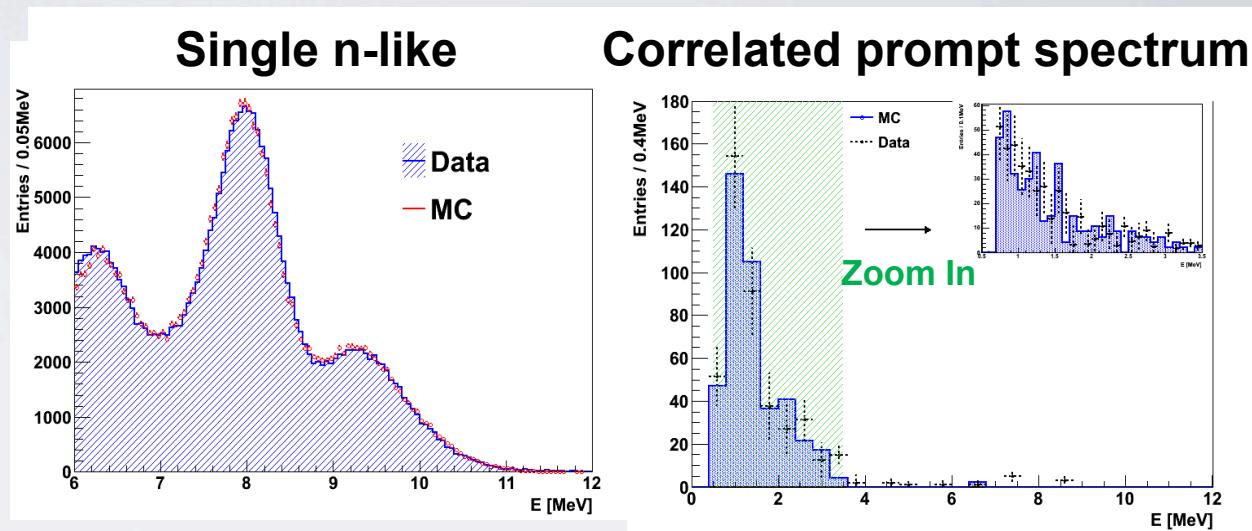
A special x80 stronger ^{241}Am - ^{13}C source placed on the AD



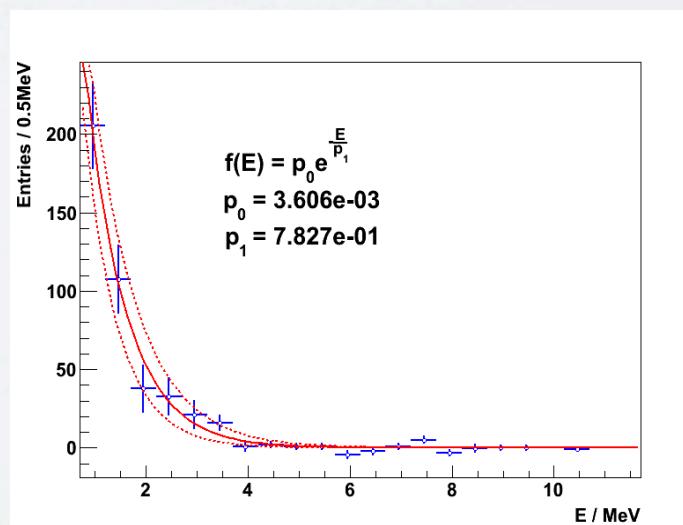
Result:

Reduced background uncertainty by a factor of 2.

Removed 2 of 3 sources in far detectors to reduce future bkgd.



Used special strong source data to benchmark and correct MC simulation



Estimation for physics data:

- Rate: 0.26/day/module (global uncert. 45%)
- Spectrum: exponential (global uncert 15%)

Challenges for the spectrum shape analysis

- Understanding Background rate and shape
- **Understanding of the detector response**
 - Energy resolution
 - Energy scale
 - Effect of inactive volume (acrylic vessel)

Understanding of Detector Response

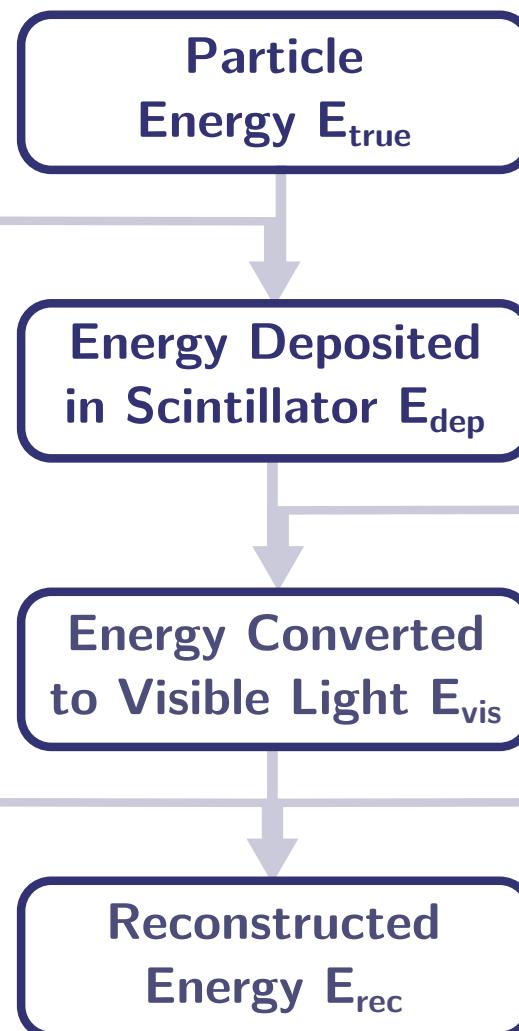
Energy Losses in Acrylic

Acrylic vessels non-scintillating

- Induce shape distortion
- Correction from MC

Energy Resolution

- Light production
- Light collection
- PMT/electronics response



Two major sources
of non-linearity.

Difficult to decouple !



1: Scintillator Response

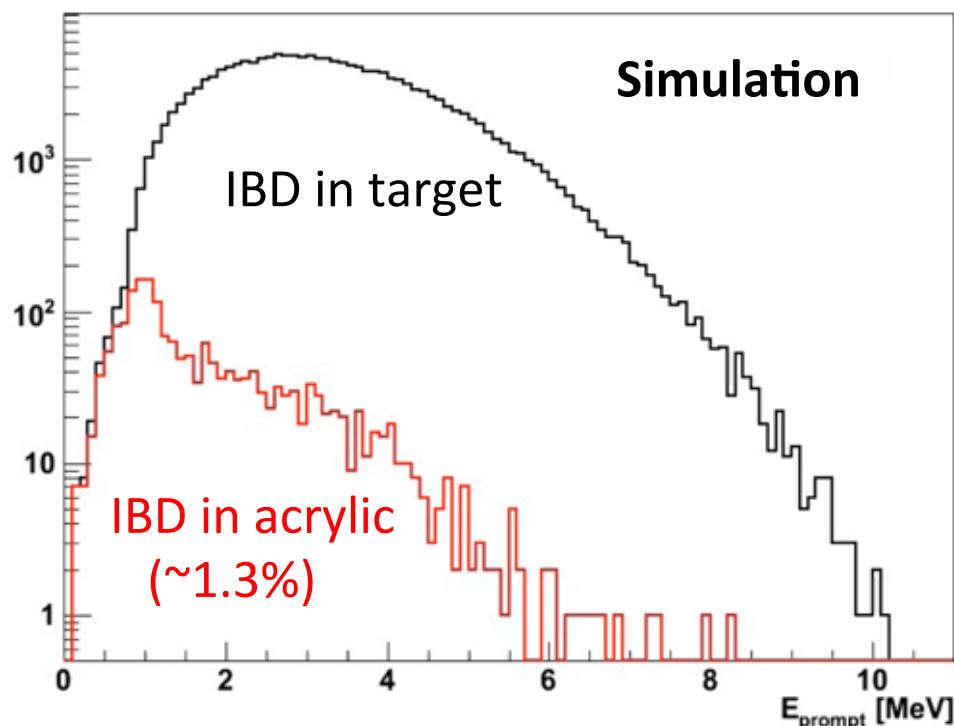
- Quenching effects
- Cherenkov radiation

2: Readout Electronics

- Charge collection efficiency decreases with visible light

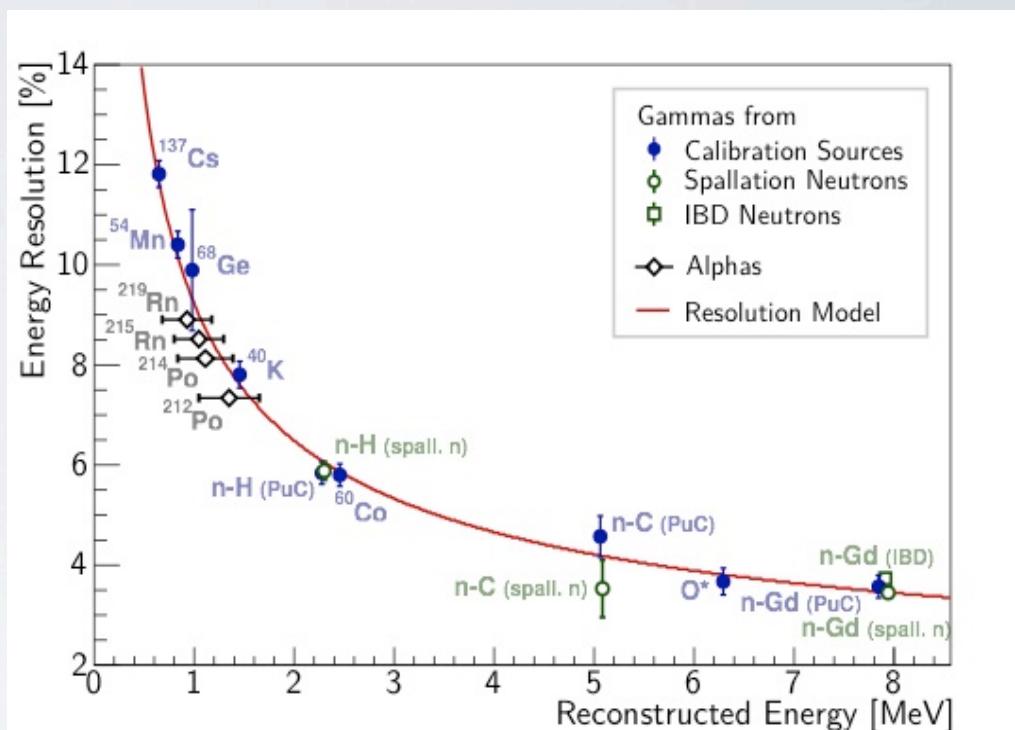
Acrylic Vessel / Energy Resolution

Energy loss in the acrylic vessel distorts spectrum



Modeled using
MC simulation

Energy resolution



$$\frac{\sigma_E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

Contributions from:

- a : Spacial/temp. resolution (E)
- b : Photon statistics (E)
- c : Dark noise (const:)

Calibrated primarily using mono-energetic gamma sources

Scintillator Response Model

Electron response

2 parameterizations to model quenching effects and Cherenkov radiation:

1) 3-parameter purely empirical model:

$$\frac{E_{\text{vis}}}{E_{\text{true}}} = \frac{1 + p_3 \cdot E_{\text{true}}}{1 + p_1 \cdot e^{-p_2 \cdot E_{\text{true}}}}$$

2) Semi-emp. model based on Birks' law:

$$\frac{E_{\text{vis}}}{E_{\text{true}}} = f_q(E_{\text{true}}; k_B) + k_C \cdot f_c(E_{\text{true}})$$

k_B : Birks' constant

k_C : Cherenkov contribution

Gammas + positrons

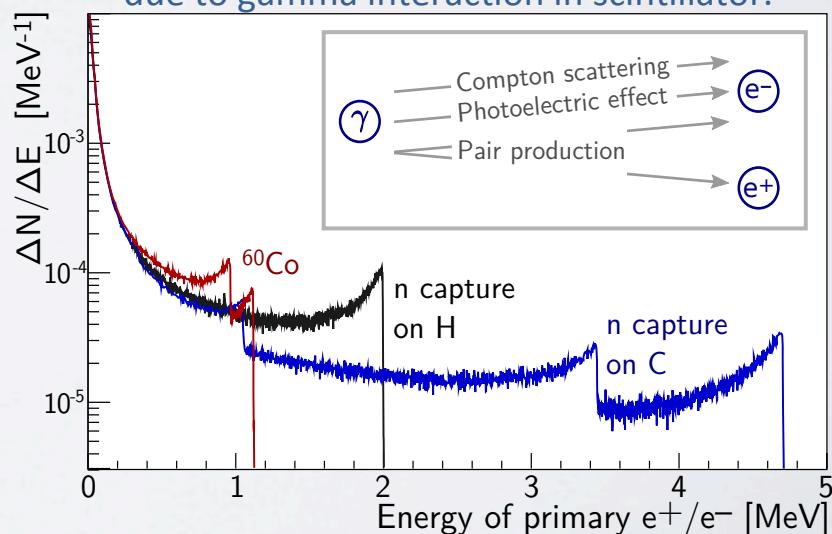
- Gammas connected to electron model through MC:

$$E_{\text{vis}}^{\gamma} = \int E_{\text{vis}}^{e^-}(E_{\text{true}}^{e^-}) \cdot \frac{dN}{dE}(E_{\text{true}}^{e^-}) dE_{\text{true}}^{e^-}$$

- Positrons connected to electron model through MC:

$$E_{\text{vis}}^{e^+} = E_{\text{vis}}^{e^-} + 2 \cdot E_{\text{vis}}^{\gamma}(0.511 \text{ MeV})$$

Simulation of individual e^- , e^+ energies due to gamma interaction in scintillator.

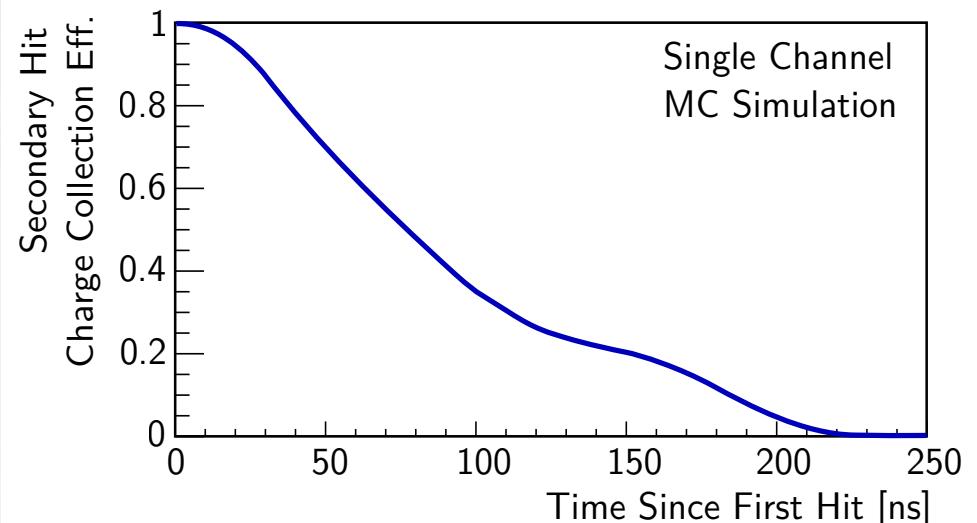


Electronics Non-Linearity Model

PMT readout electronics introduces additional biases

Electronics does not fully capture late secondary hits

- Slow scintillation component missed at high energies
- Charge collection efficiency decreases with visible light



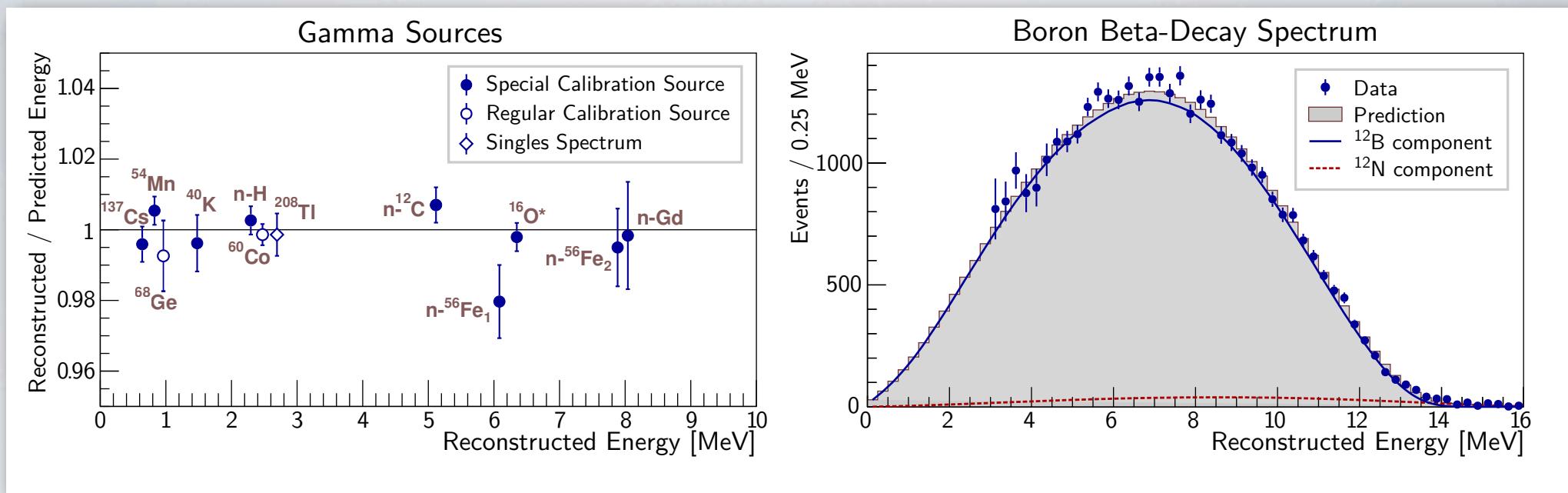
Observed non-linearity is a product of scintillator and electronics non-linearity

$$f = \frac{E_{\text{rec}}}{E_{\text{true}}} = \frac{E_{\text{vis}}}{E_{\text{true}}} \times \frac{E_{\text{rec}}}{E_{\text{vis}}} = f_{\text{scint}}(E_{\text{true}}) \times f_{\text{elec}}(E_{\text{vis}})$$

1 Scintillator non-linearity
2 Electronics non-linearity

Constrained the model with full use of current existing data...

Constraining Non-Linearity Parameters



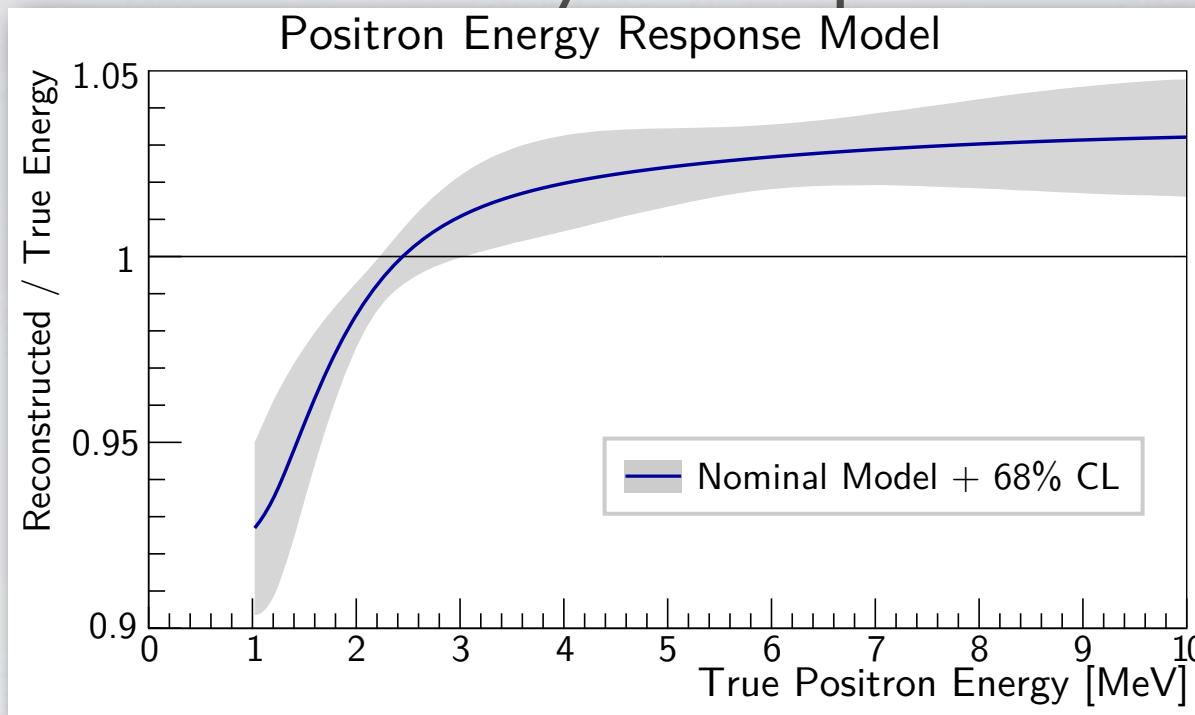
Full detector calibration data

1. Monoenergetic gamma lines from various sources
 - Radioactive calibration sources, employed regularly: ^{68}Ge , ^{60}Co , ^{241}Am - ^{13}C and during special calibration periods: ^{137}Cs , ^{54}Mn , ^{40}K , ^{241}Am - ^{9}Be , Pu - ^{13}C
 - Singles and correlated spectra in regular physics runs (^{40}K , ^{208}Tl , n capture on H)
2. Continuous spectrum from ^{12}B produced by muon spallation inside the scintillator

Standalone measurements

- Scintillator quenching measurements using neutron beams and Compton e^-
- Calibration of readout electronics with flash ADC

Final Positron Energy Non-Linearity response



Several validated models

- Constructed based on different parameterizations/weighting of data constraints
- All models in good agreement with detector calibration data
- Resulting positron non-linearity curves consistent within $\sim 1.5\%$ uncertainty

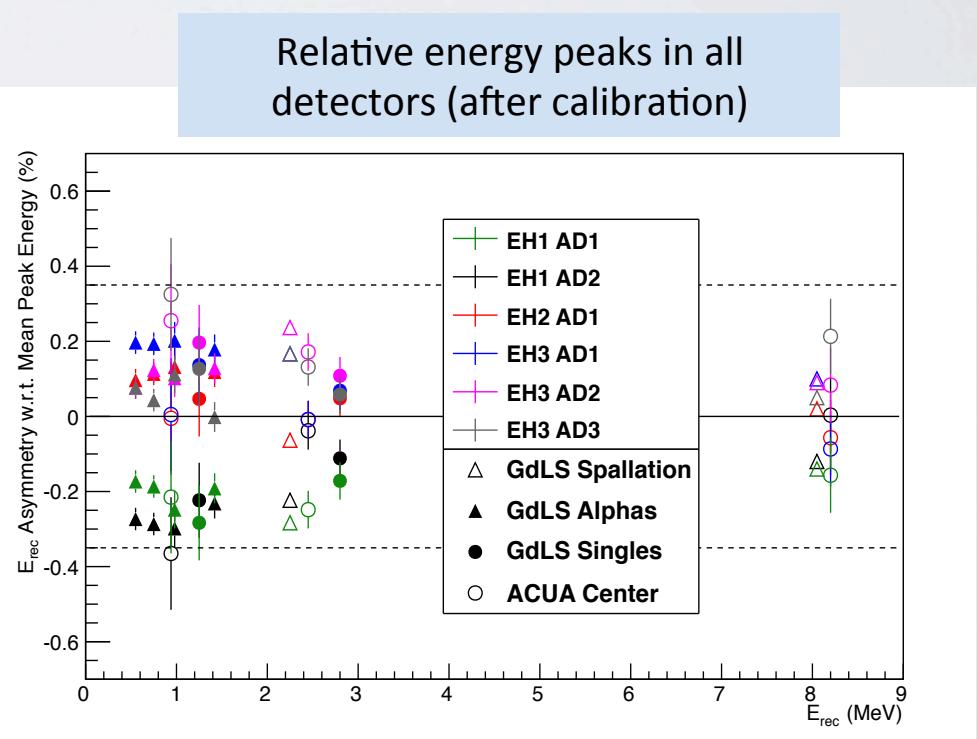
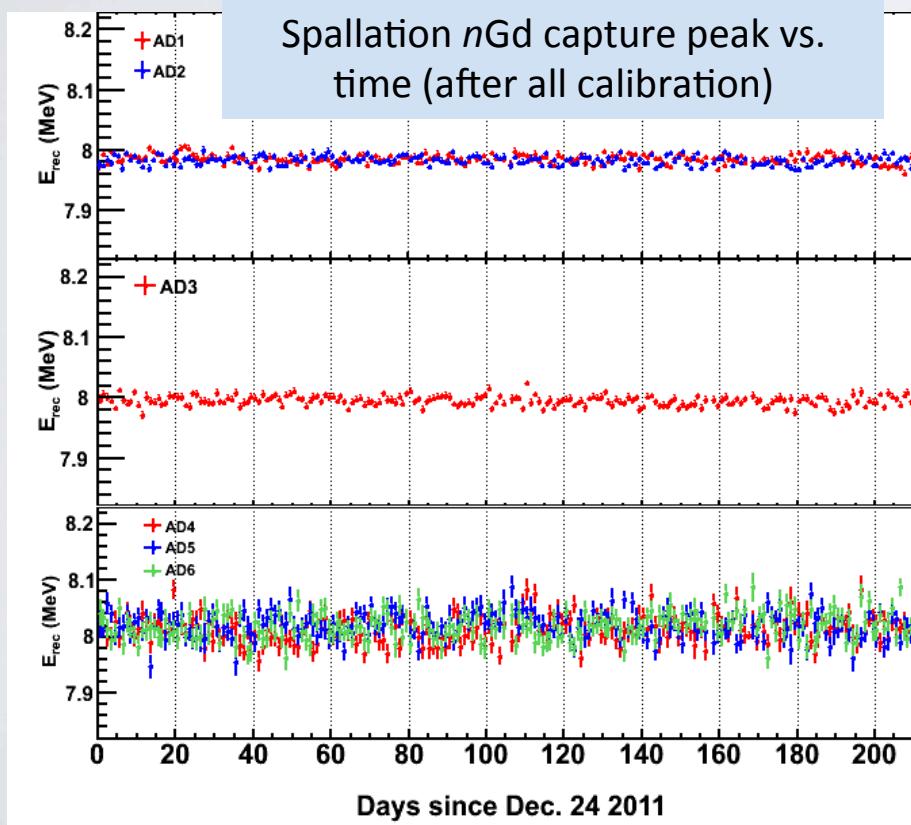
Used combination of 5 models to conservatively estimate uncertainty

Relative Energy Scale

Crucial ingredient: Consistent energy response for all ADs

Careful calibration with in-situ data and calibration sources:

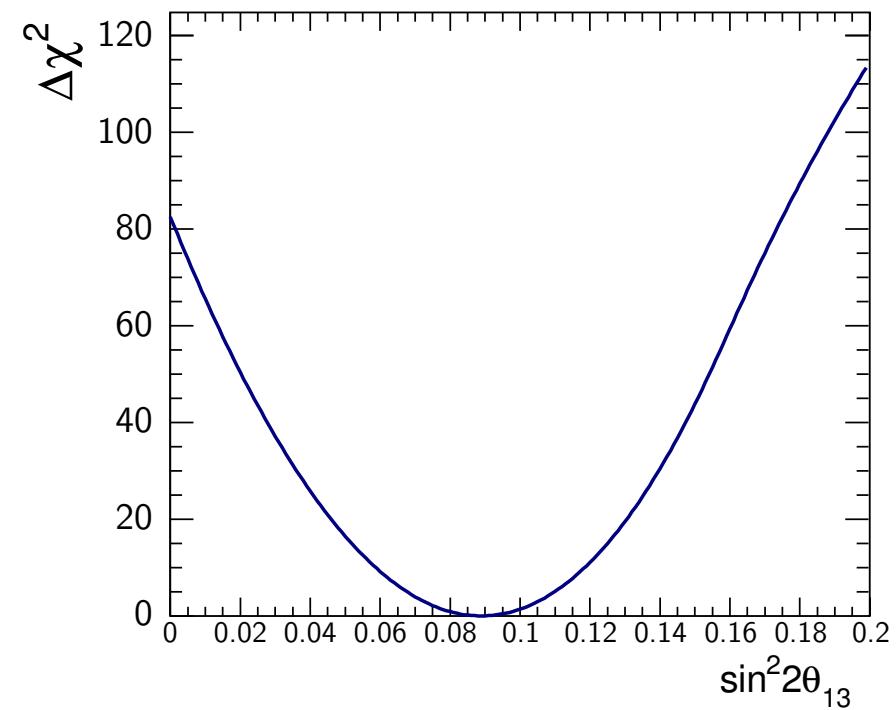
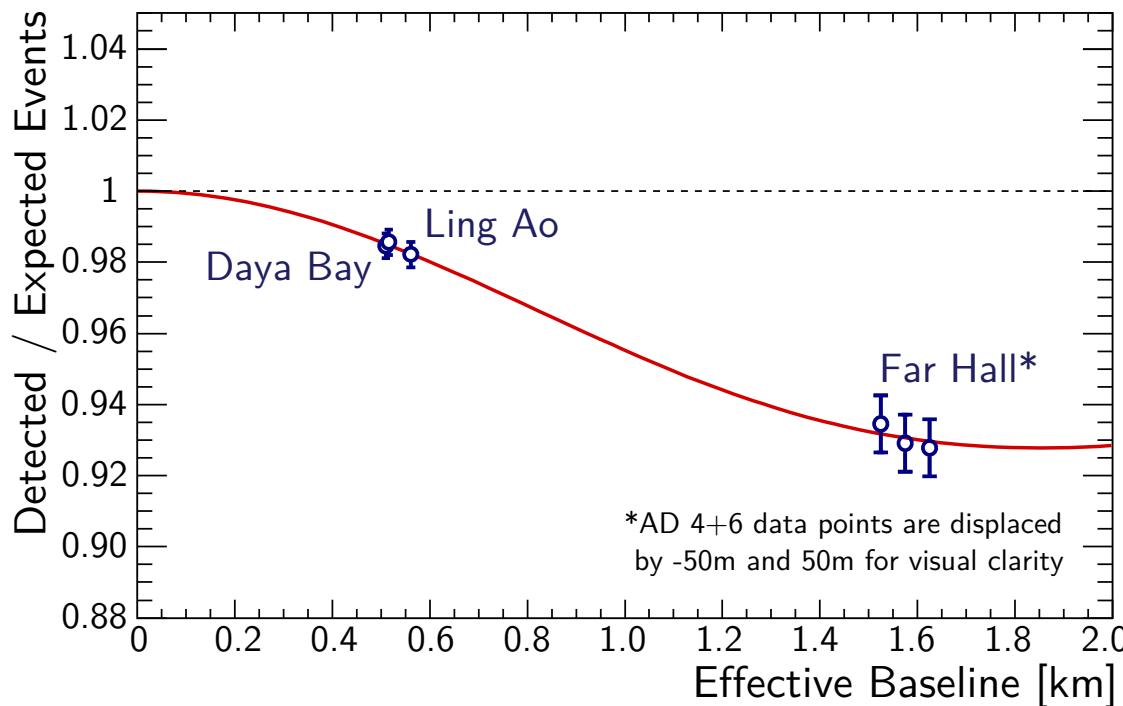
- Energy response stable to 0.1% in all detectors
- Total relative uncertainty of 0.35% between detectors



Yet, the largest source of systematic uncertainty for Δm^2_{ee}

Results

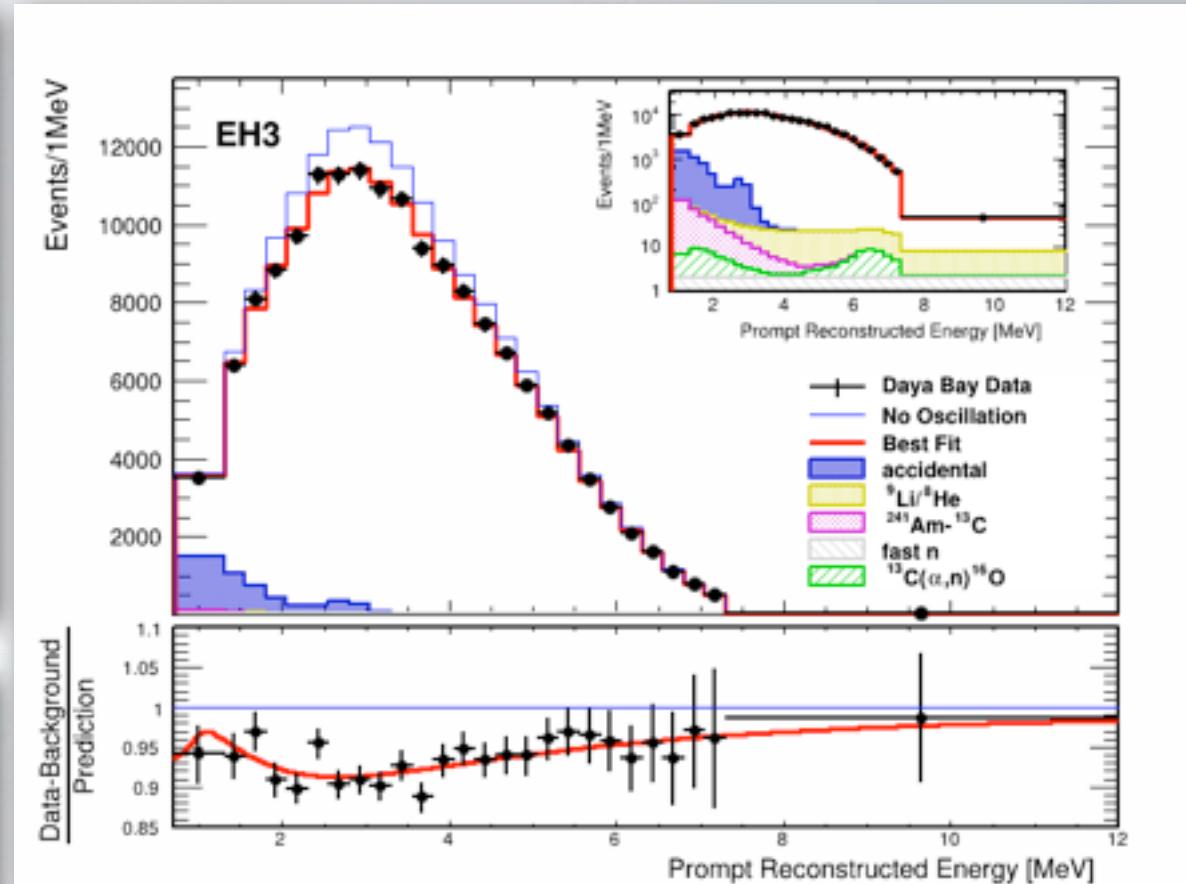
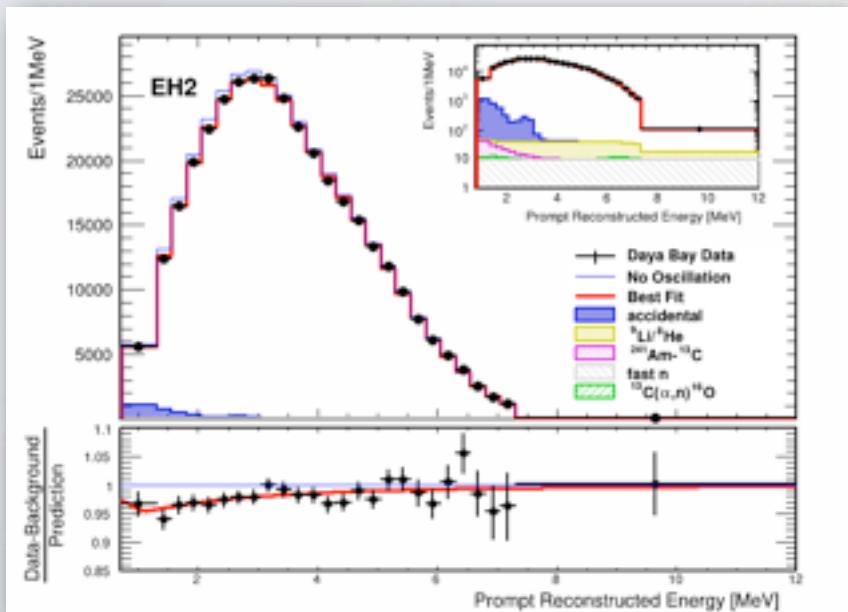
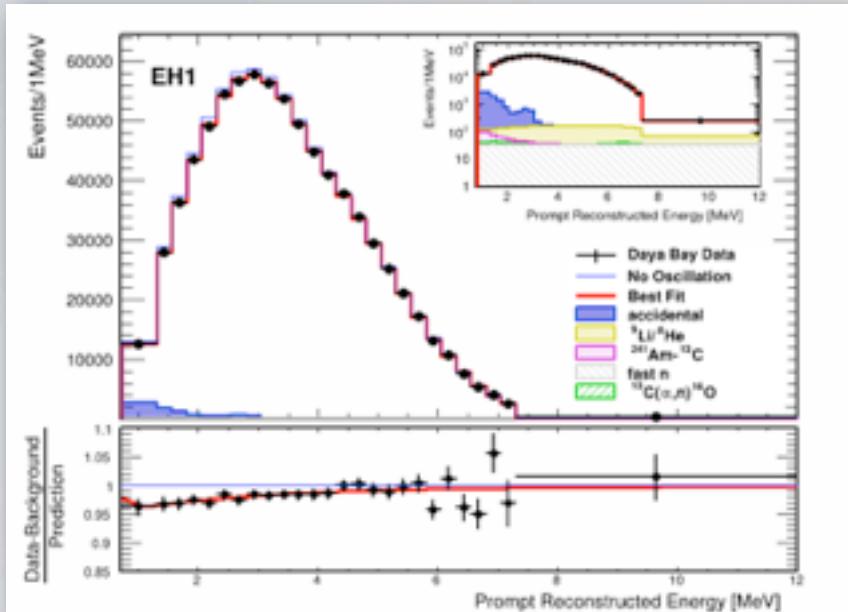
Rate only analysis



$$\sin^2 2\theta_{13} = 0.089 \pm 0.009 \quad \chi^2/N_{\text{DOF}} = 0.48/4$$

- Uncertainty reduced by statistics of complete 6 AD data period
- $|\Delta m^2_{ee}|$ constrained by MINOS result: $|\Delta m^2_{\mu\mu}| = 2.41^{+0.09}_{-0.10} \times 10^{-3} \text{ eV}^2$
PRL. 110, 251801 (2013)
- Far vs. near relative measurement: absolute rate not constrained
- Consistent results from independent analysis, different reactor models

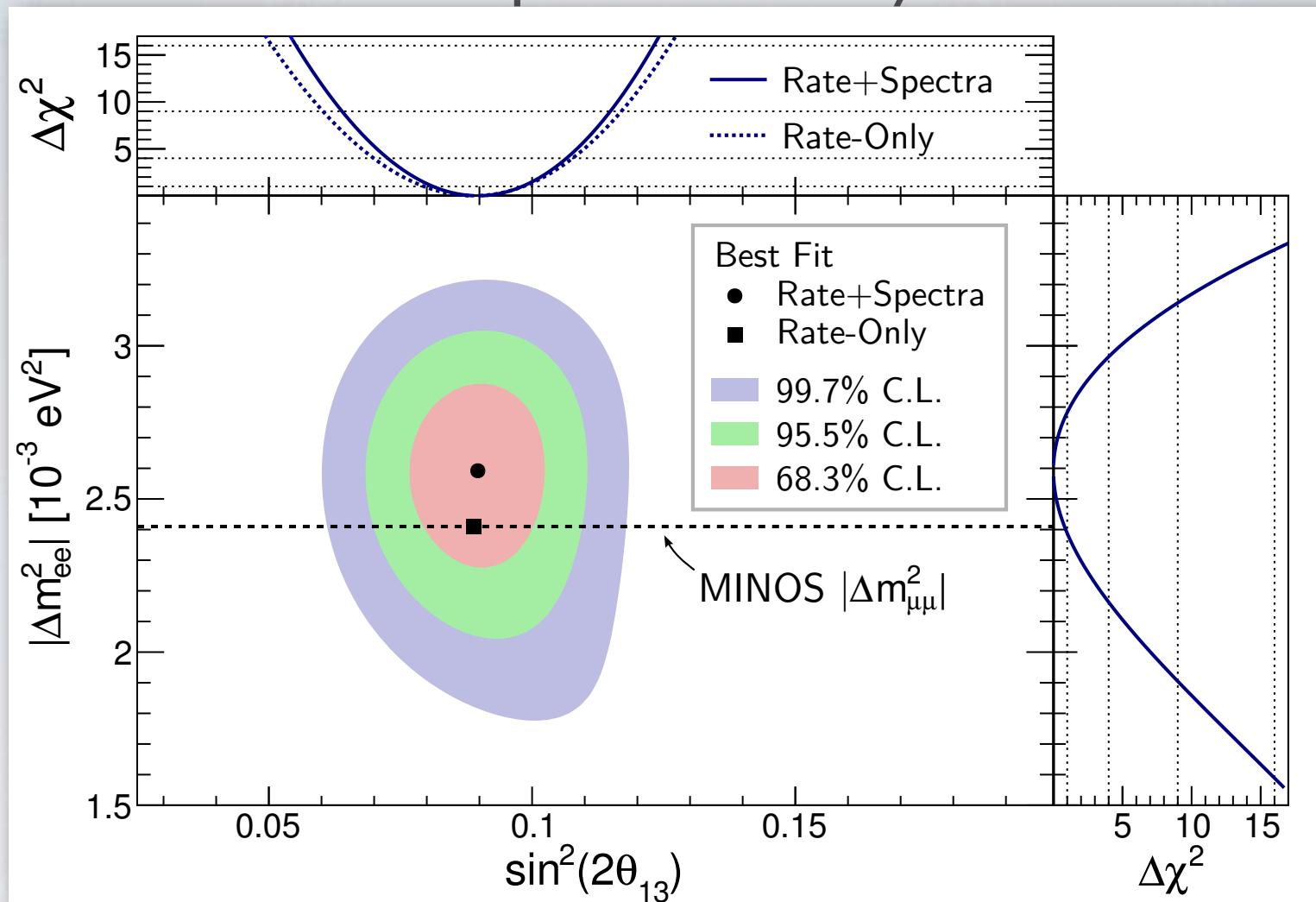
IBD Prompt Energy Spectra



*Spectral distortion
consistent with oscillation*

- Both background and predicted no oscillation spectra determined by the best fit
- Errors are statistical only

Rate and Shape Analysis Results

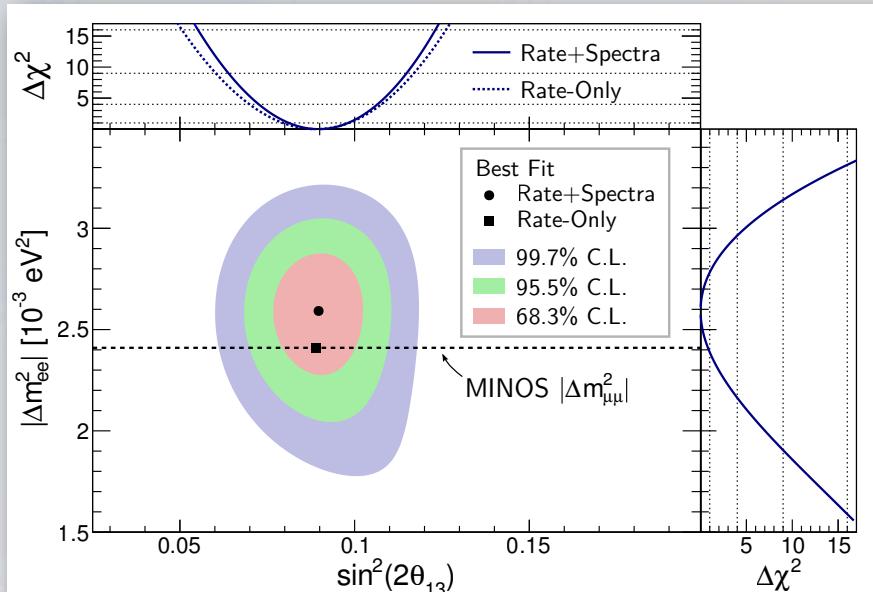


$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

$$\chi^2/N_{\text{DOF}} = 162.7/153$$

$$|\Delta m_{ee}^2| = 2.59^{+0.19}_{-0.20} \times 10^{-3} \text{ eV}^2$$

Rate and Shape Analysis Results



$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

$$|\Delta m_{ee}^2| = 2.59^{+0.19}_{-0.20} \times 10^{-3} \text{ eV}^2$$

$$\chi^2/N_{\text{DOF}} = 162.7/153$$

Strong confirmation of the oscillation model

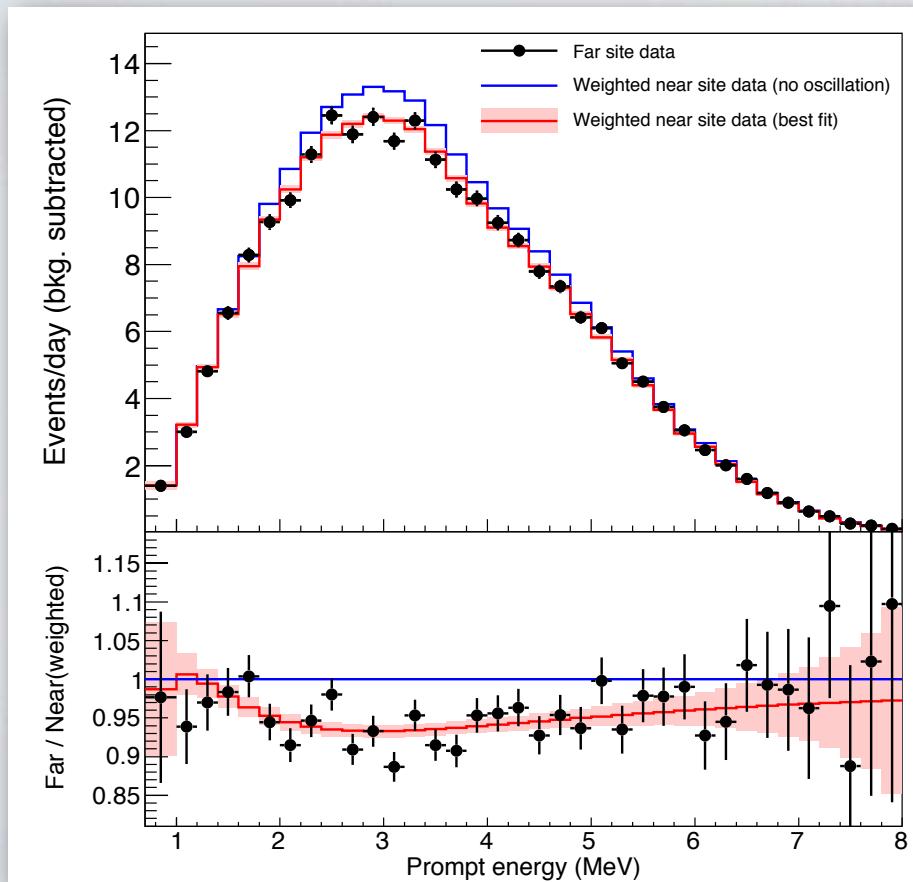
	Normal MH Δm_{32}^2 [10^{-3} eV 2]	Inverted MH Δm_{32}^2 [10^{-3} eV 2]
From Daya Bay Δm_{ee}^2	$2.54^{+0.19}_{-0.20}$	$-2.64^{+0.19}_{-0.20}$
From MINOS $\Delta m_{\mu\mu}^2$ [João, NuFact2013]	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.12}_{-0.09}$

Near vs. Far Spectrum study

Independent crosscheck with minimal reactor assumption

Predict far spectra directly from measured near site spectra

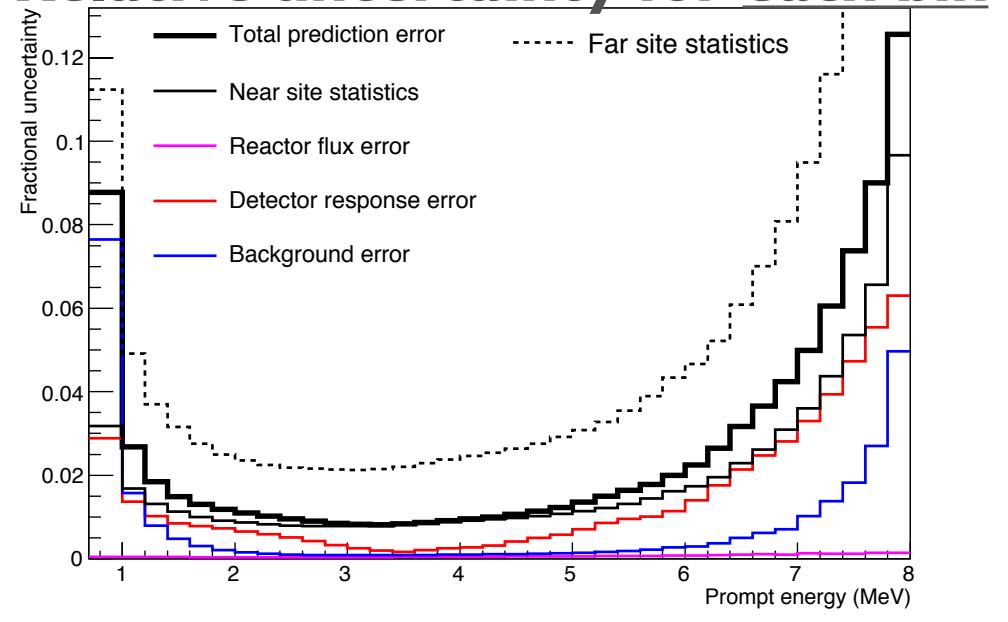
→ Minimizes impact of absolute flux and spectra prediction.



Use covariance matrices to account for systematic errors

→ Alternate method finds consistent uncertainties for neutrino parameters.

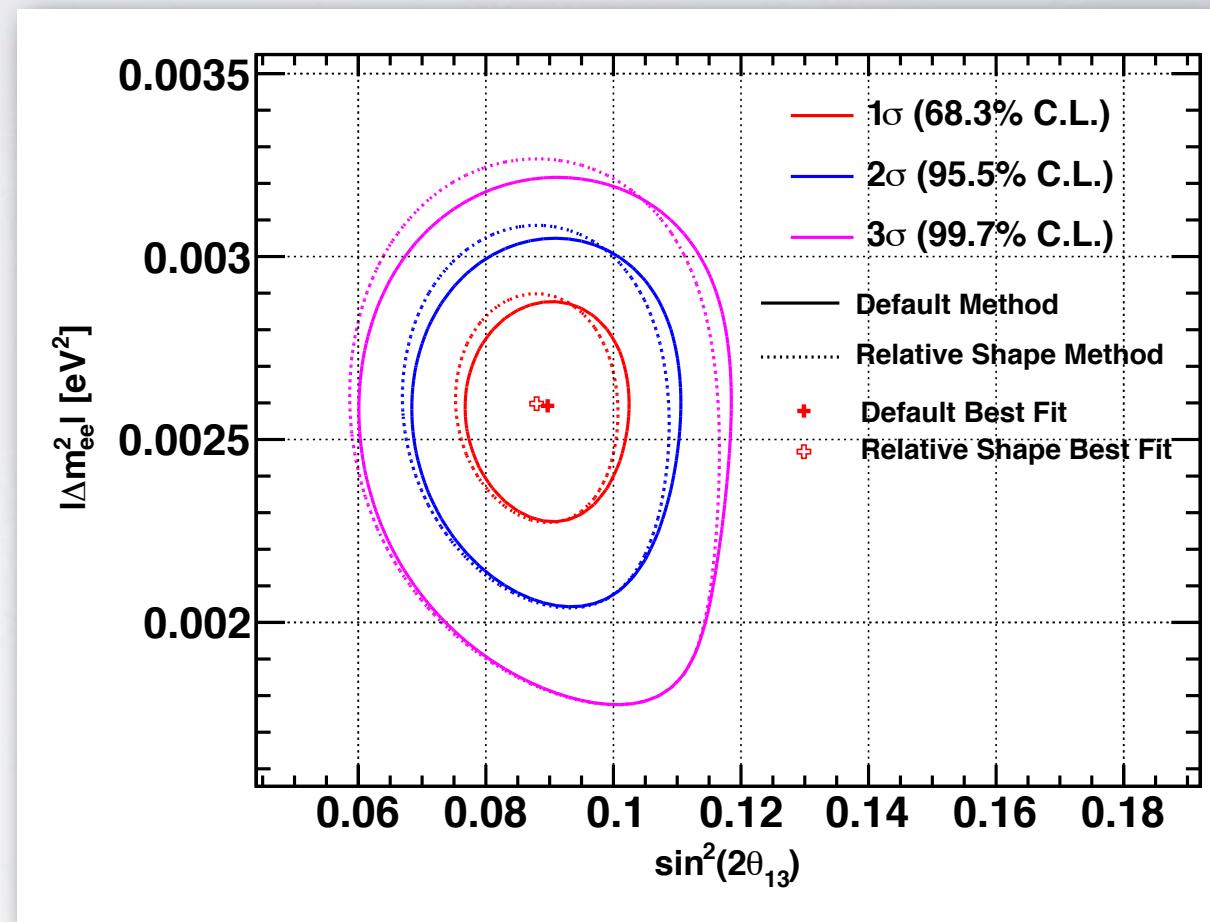
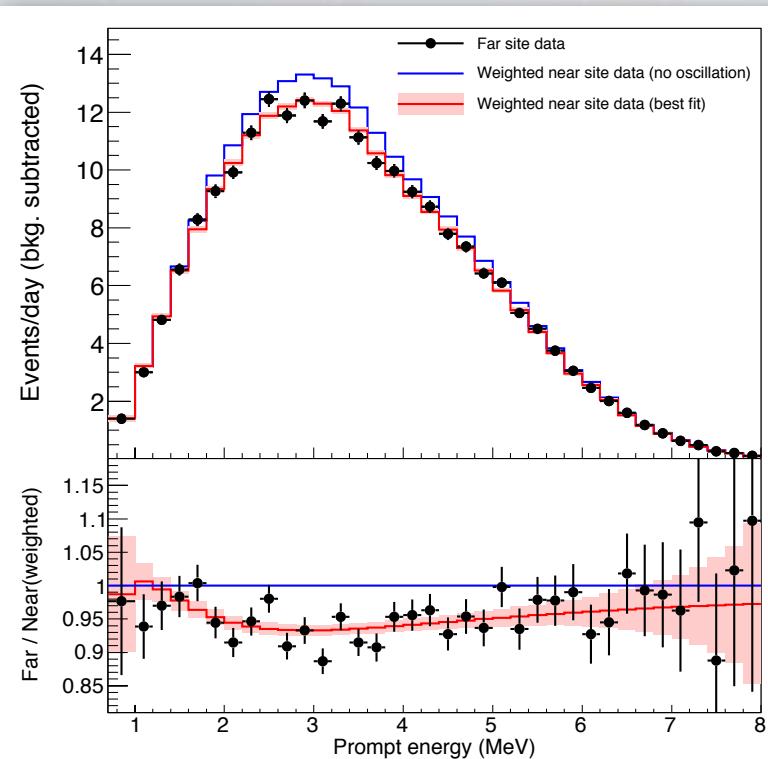
Relative uncertainty for each bin



Systematic uncertainties controlled to well below statistical error

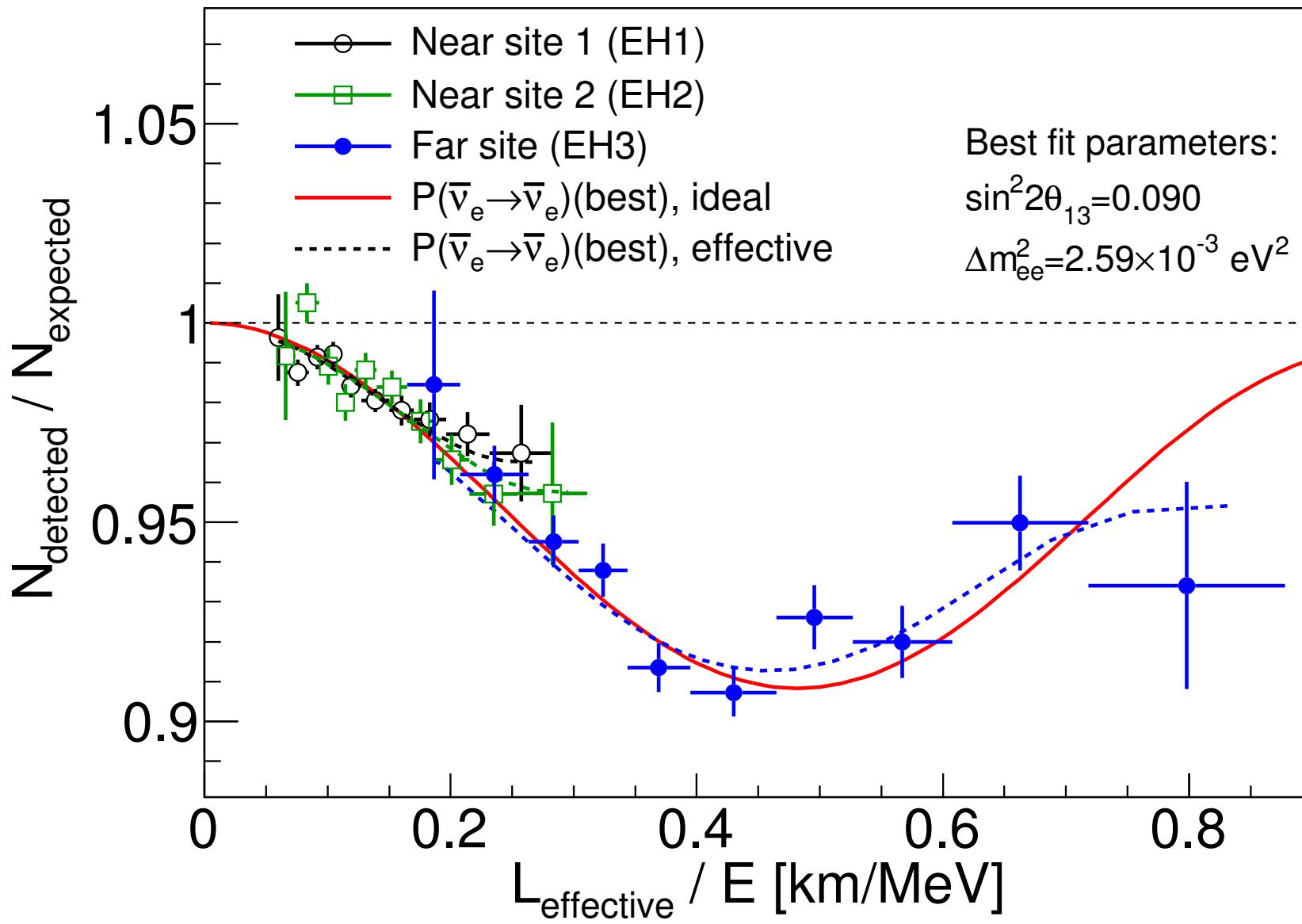
Near vs. Far Spectrum Study

Fit Result



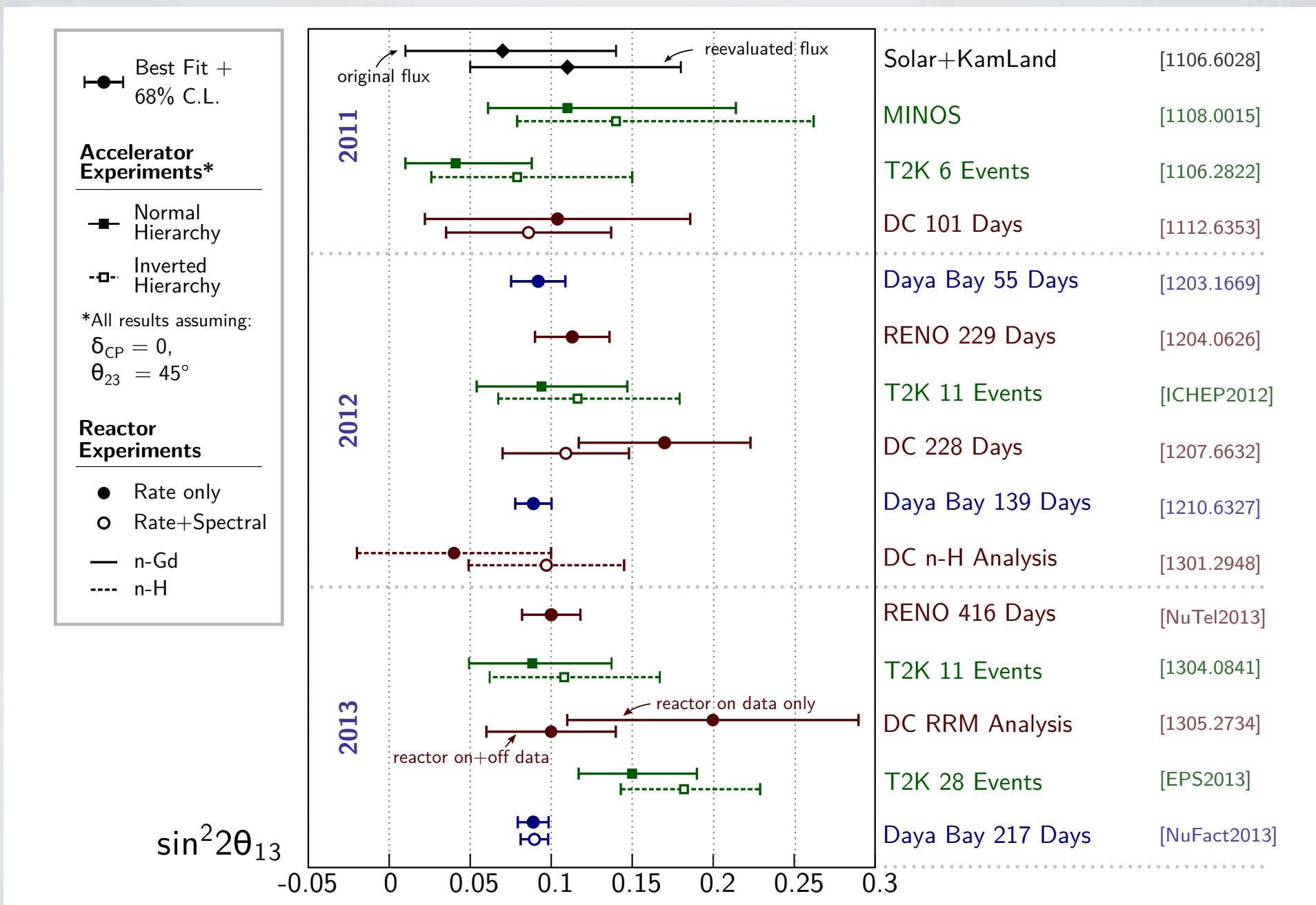
Consistent results with the default method

Neutrino Oscillates



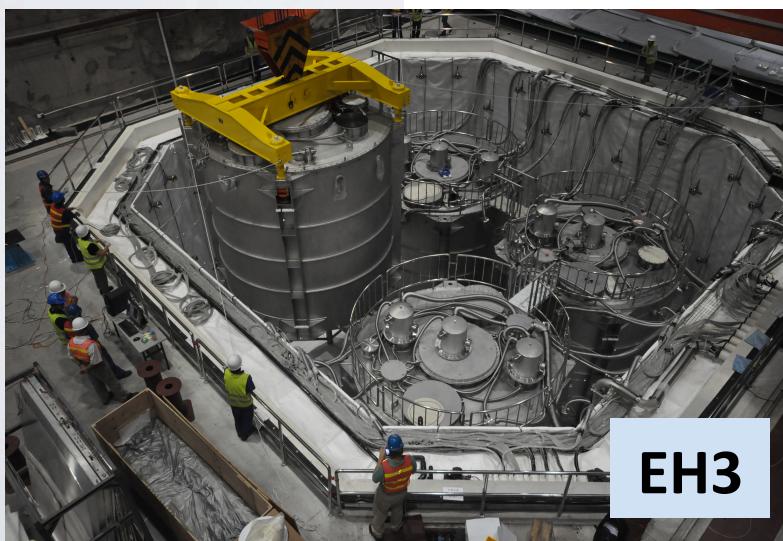
Effective curves include effects of multiple baseline and detector resolution

Global Comparison of θ_{13} Measurements

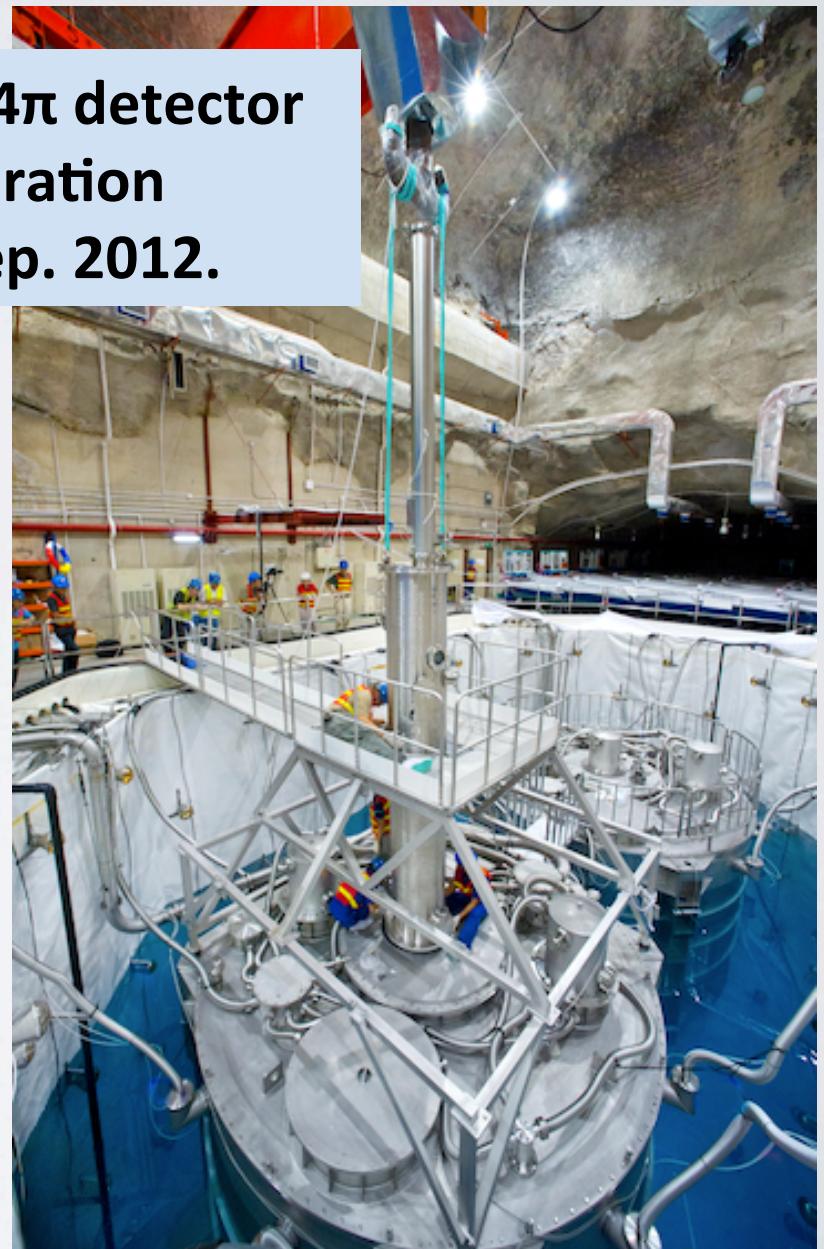


Daya Bay Onsite Progress

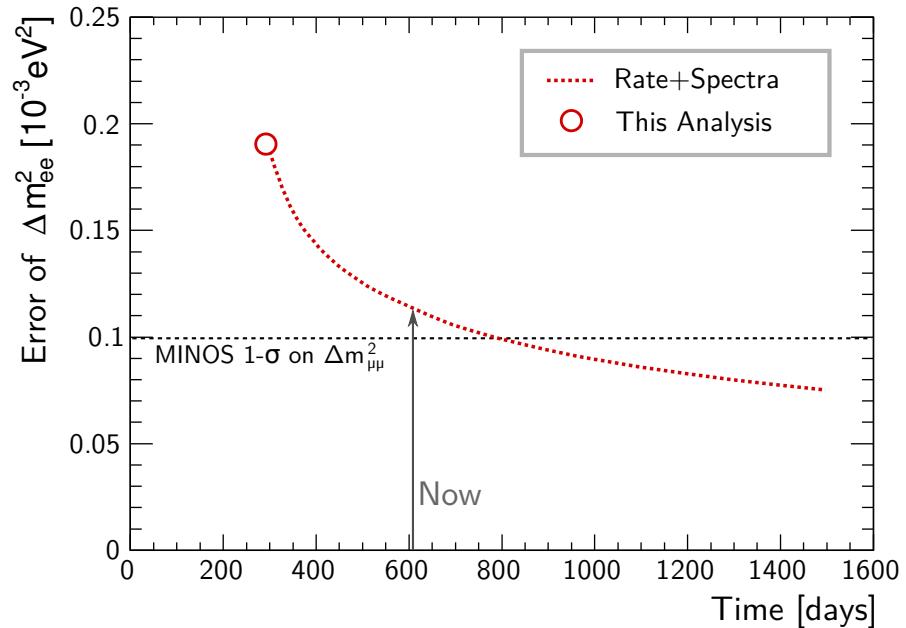
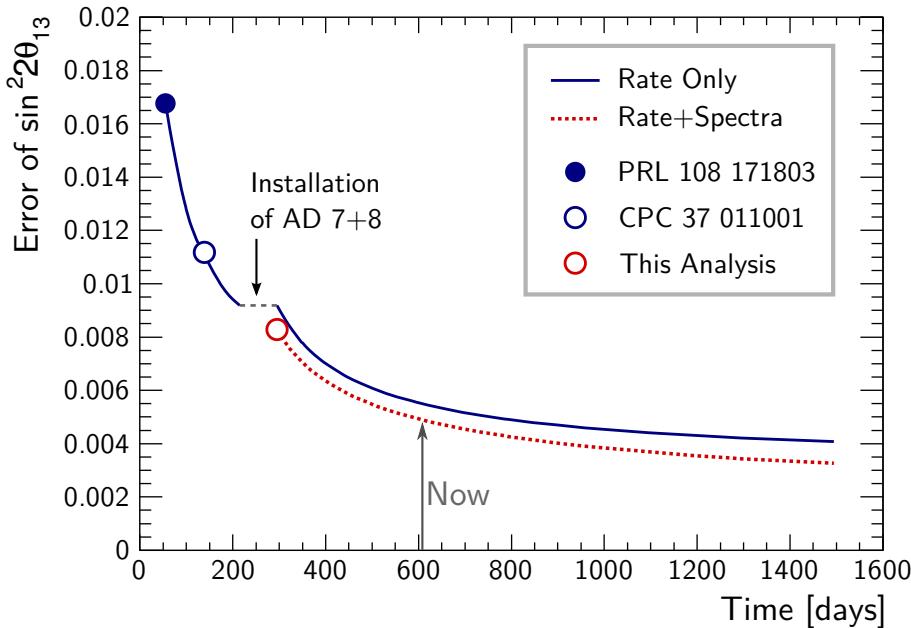
**Final two detectors installed,
operating since Oct. 2012.**



**Full 4π detector
calibration
in Sep. 2012.**



Future Sensitivity



Sensitivity still dominated by statistics

- Statistics contribute 73% (65%) to total uncertainty in $\sin^2 2\theta_{13}$ ($|\Delta m^2_{ee}|$)
- Major systematics:
 - θ_{13} : Reactor model, relative + absolute energy, and relative efficiencies
 - $|\Delta m^2_{ee}|$: Relative energy model, relative efficiencies, and backgrounds
- Precision of mass splitting measurement closing in on results from μ flavor sector

Summary

- The Daya Bay Experiment has made the first direct measurement of the short-distance electron antineutrino oscillation frequency:

$$|\Delta m_{ee}^2| = 2.59^{+0.19}_{-0.20} \times 10^{-3} \text{ eV}^2$$

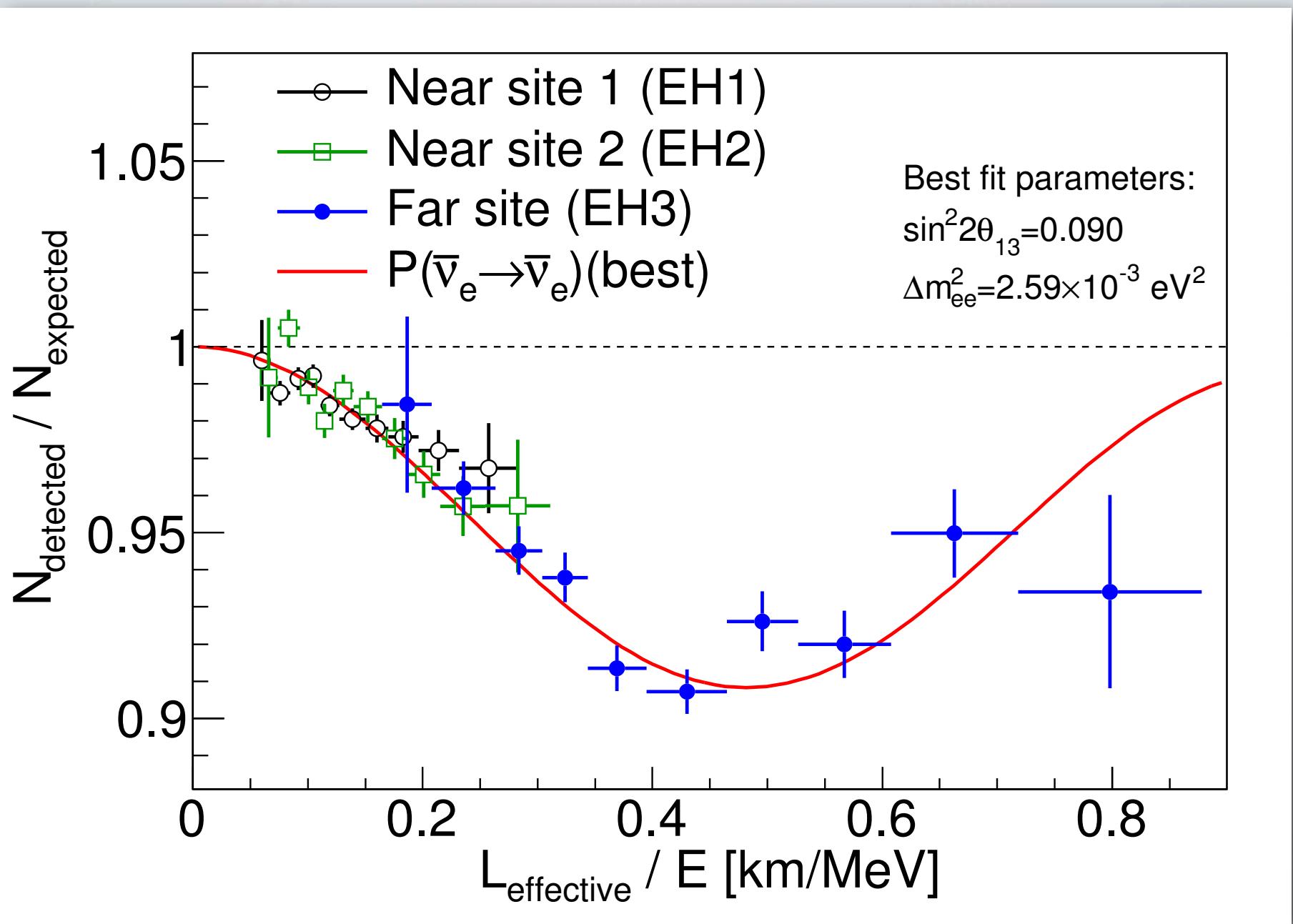
- We also produced the most precise estimate of the mixing angle:

$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

- Still, a lot of results coming in the near future:
 - Measurement of absolute reactor flux
 - Testing non-standard neutrino models
 - Significantly increased precision with much more statistics

Backup slides

Neutrino Oscillates



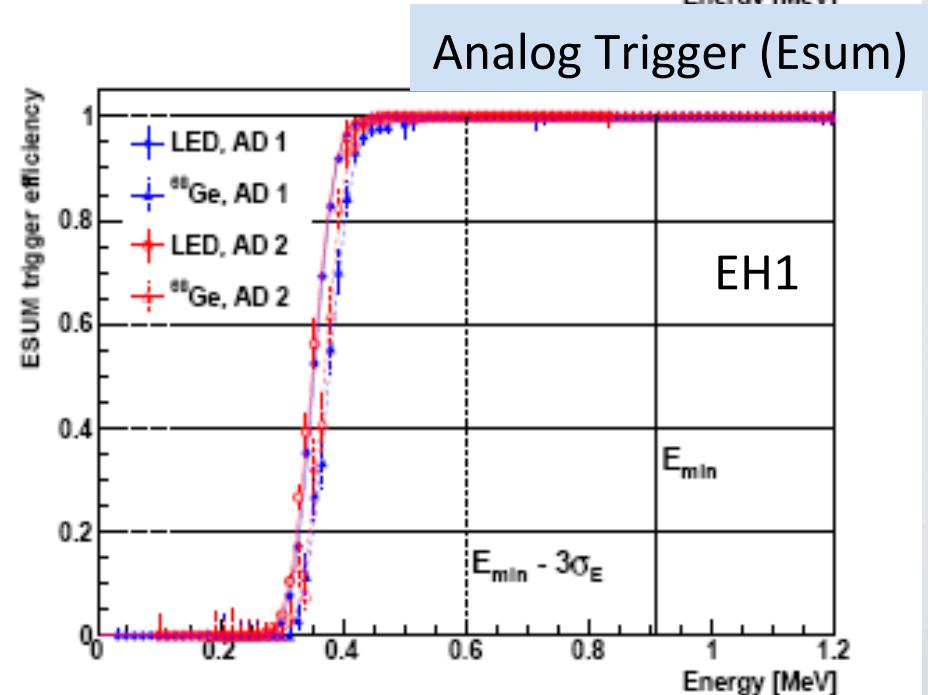
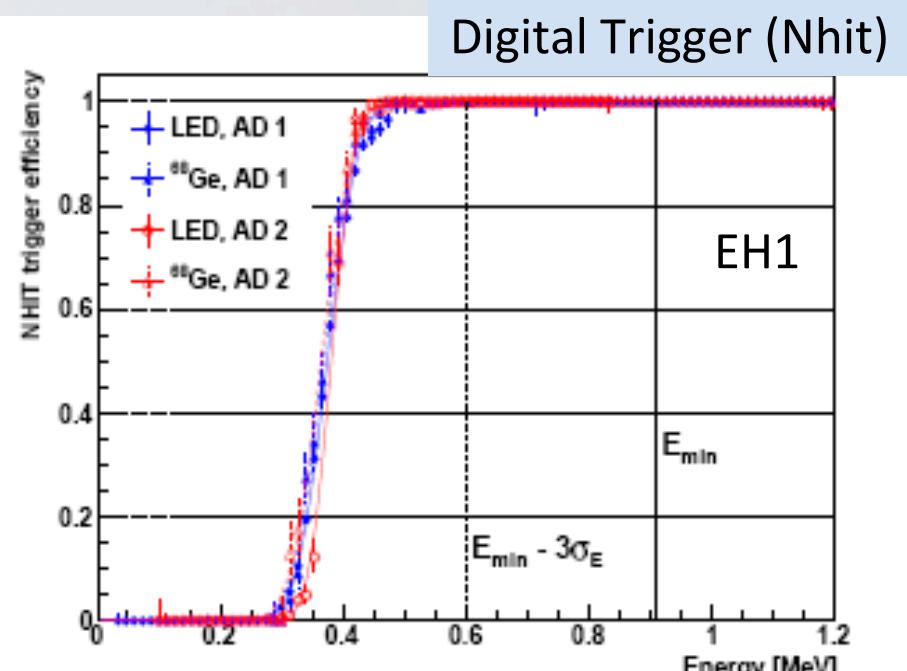
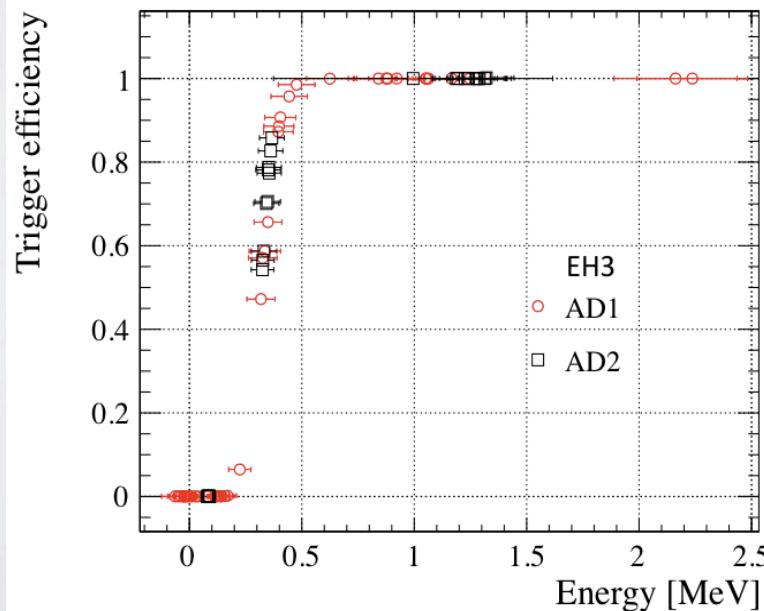
Trigger Performance

Trigger Thresholds:

- AD: >45 PMTs (digital trigger)
 >0.4 MeV (analog trigger)
- Inner Water Veto: > 6 PMTs
- Outer Water Veto: >7 PMTs
- RPC: $\frac{3}{4}$ layers in module

Trigger Efficiency:

- No measurable inefficiency >0.7 MeV
- Minimum energy expected for prompt antineutrino signal is \sim 0.9 MeV.

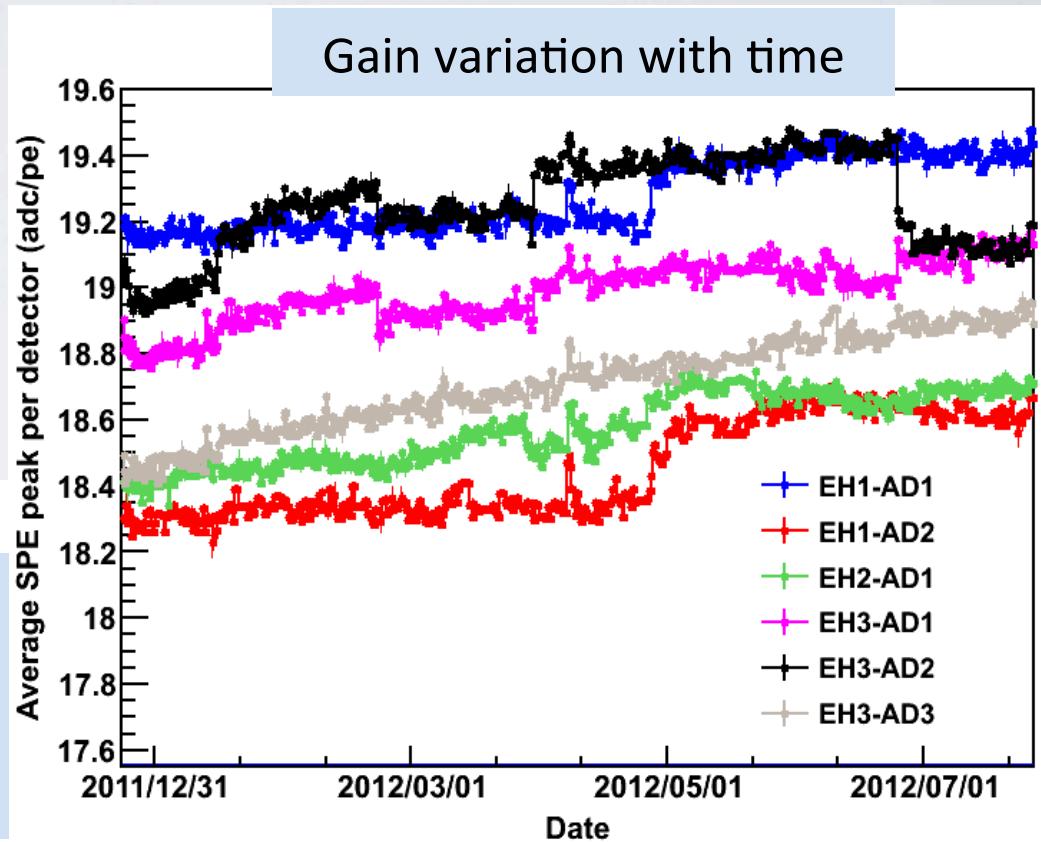
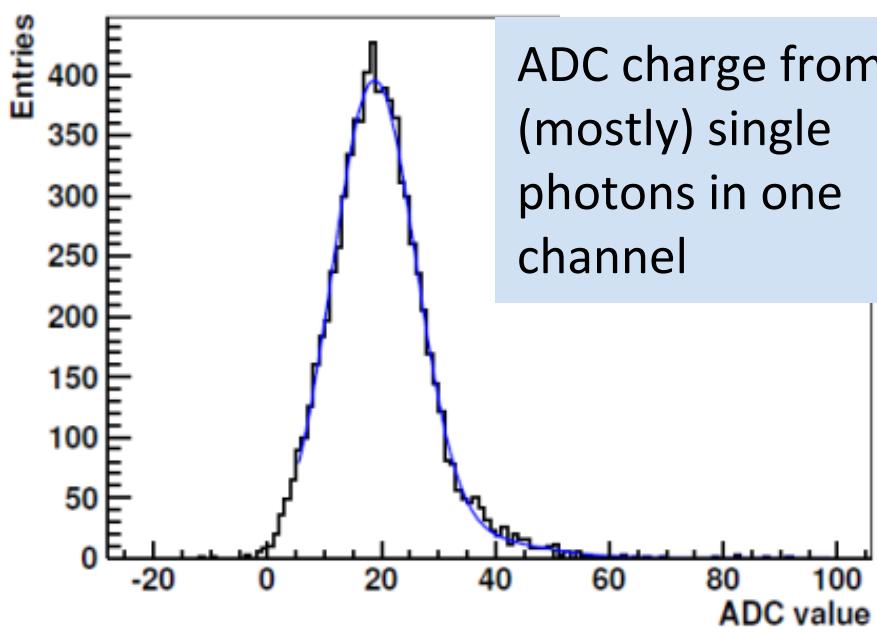


Calibration: PMT+Electronics Gain

Measure charge from single photons in-situ with data

Use out-of-time PMT signals hits to calibrate the PMT + electronics response to single photons.

Cross-check with weekly LED deployments.



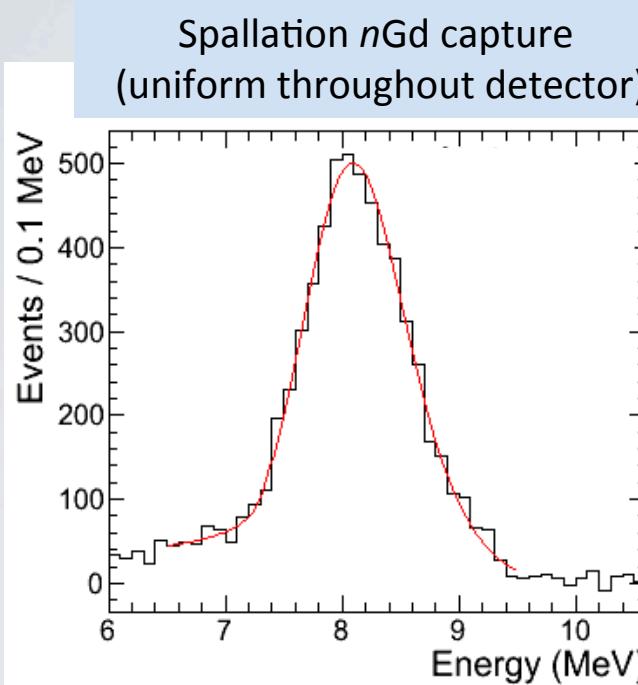
Calibration driven by uncertainty in relative detector efficiency

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}} \right) \left(\frac{L_n}{L_f} \right)^2 \left(\frac{\epsilon_f}{\epsilon_n} \right) \left[\frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)} \right]$$

Calibration: Energy Scale

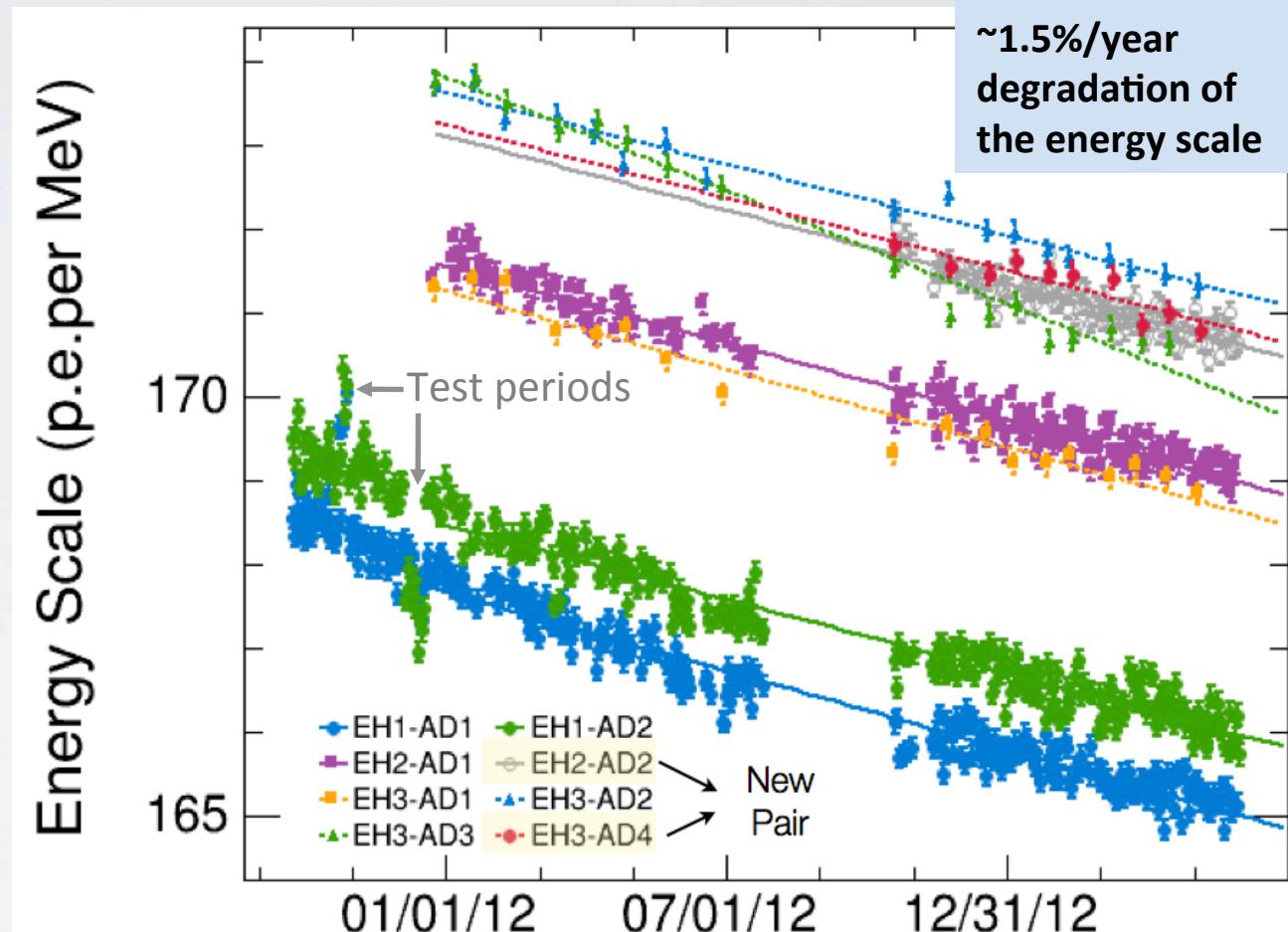
Measure energy scale in-situ with data

Calibrate charge (photoelectrons) collected per MeV in-situ using spallation nGd capture events. Also use weekly deployments of ^{60}Co source.



$$\text{Energy Scale} = Q / E$$

Measured charge of nGd peak Average energy released in nGd

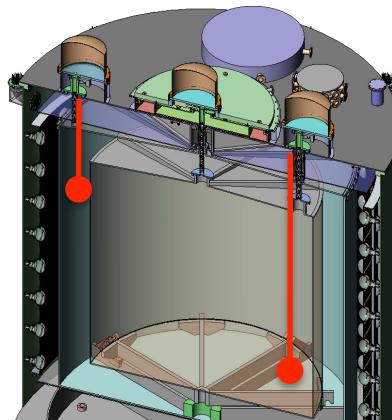


Small degradation of energy scale is seen with nGd, ^{60}Co , and other event types. Its origin is still unknown, but do not anticipate any problems in experiment's lifetime.

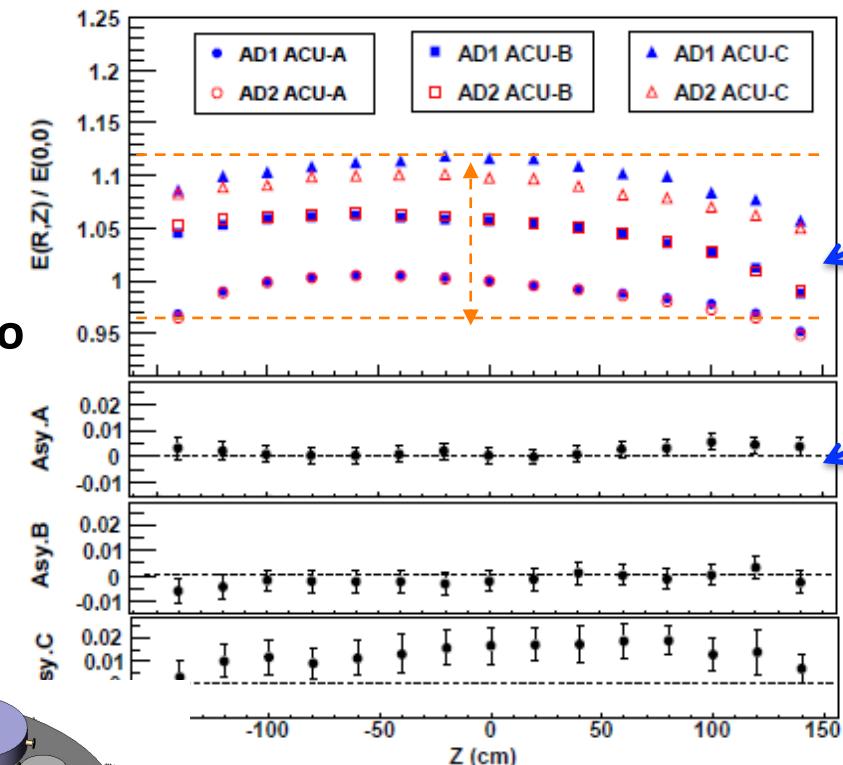
Calibration: Detector Uniformity

Measure uniformity with sources placed along three axes and spallation nGd events

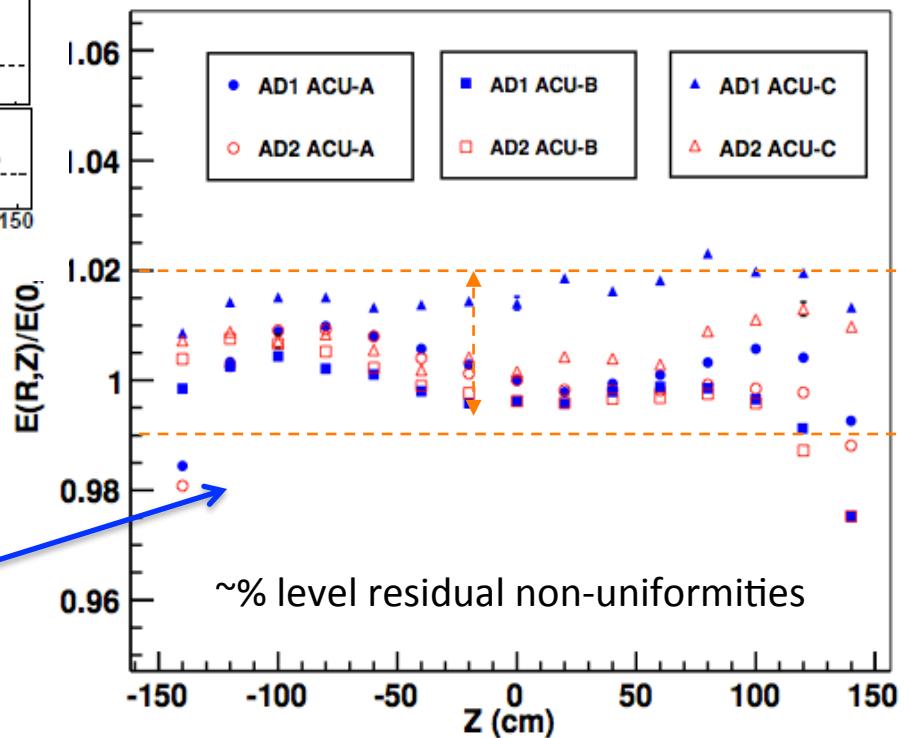
Example: ^{60}Co



3 sources along 3 axes



After first-order correction, energy is more uniform.



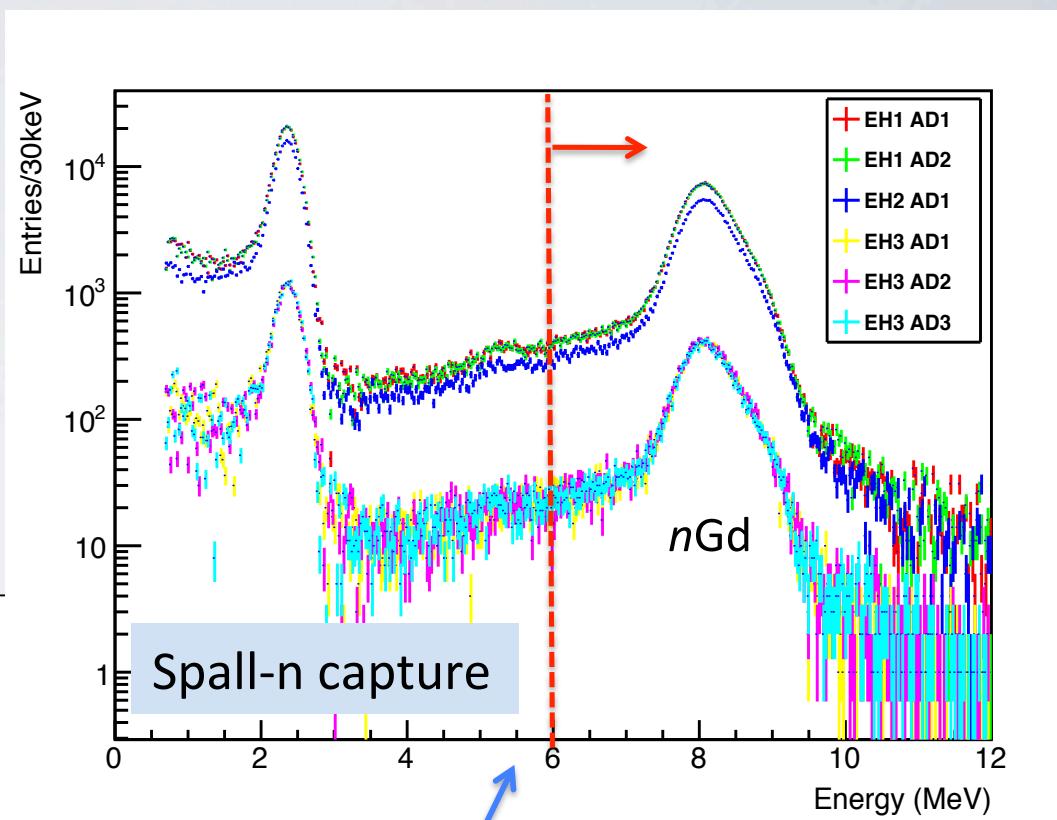
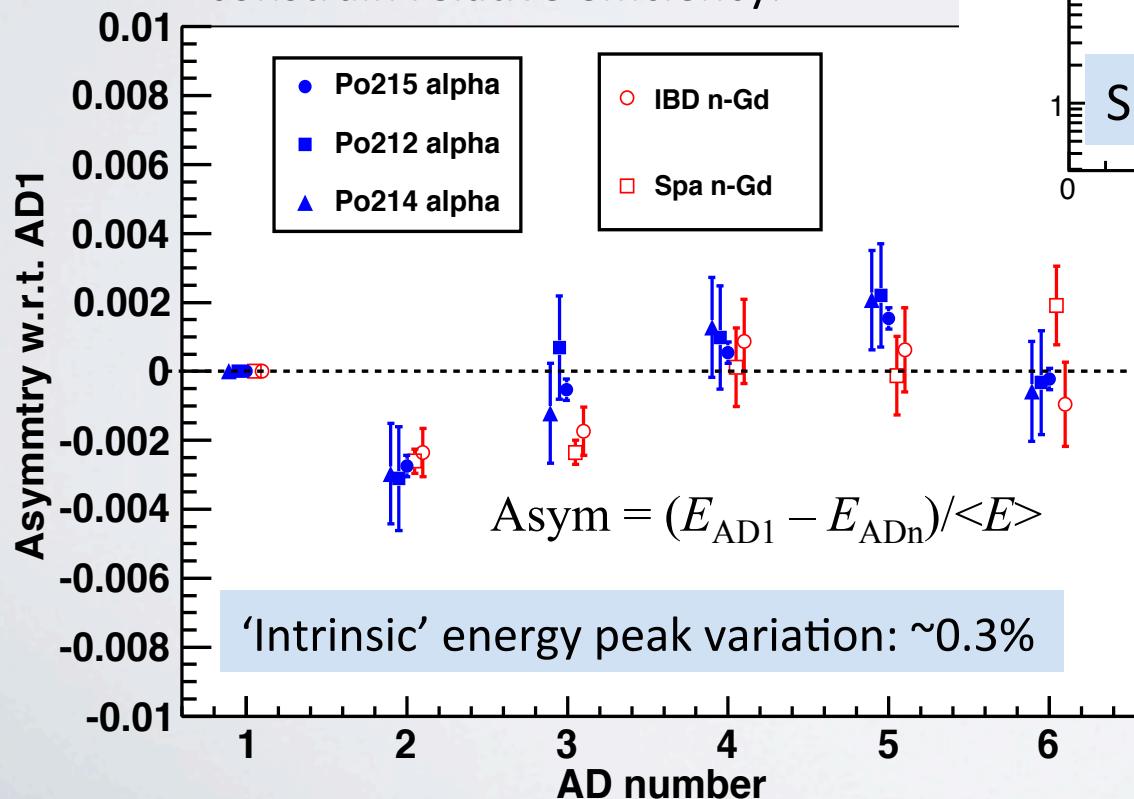
Energy response varies across detector...
...but still consistent between detectors

Delayed Energy Cut

Largest uncertainty between detectors

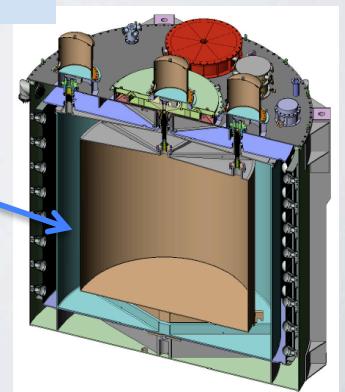
Some n Gd gammas escape scintillator region, visible as tail of n Gd energy peak.

Use variations in energy peaks to constrain relative efficiency.



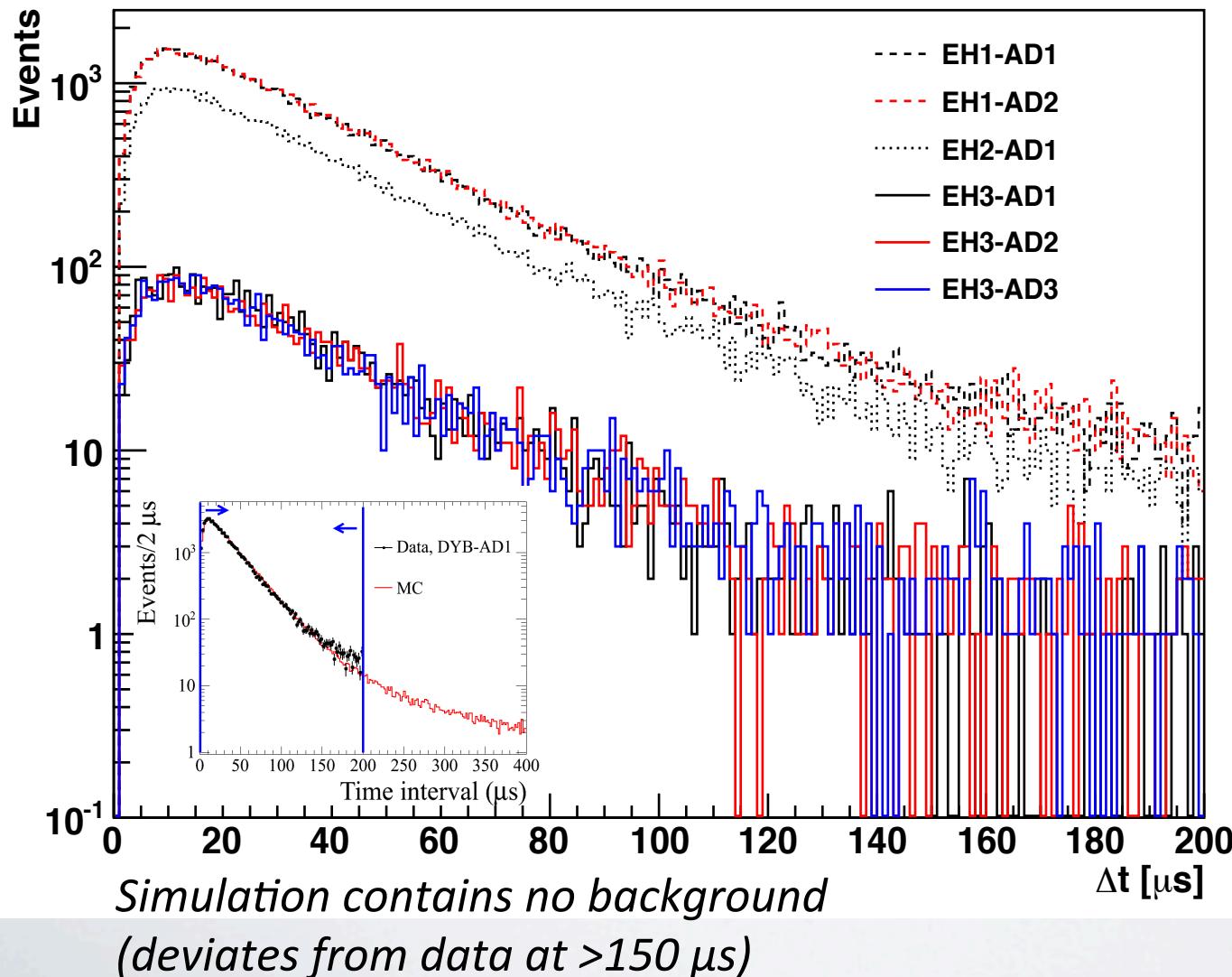
Efficiency variations
estimated at 0.12%

Motivation
for
3-zone design



Capture Time

Consistent IBD neutron capture time measured in all detectors

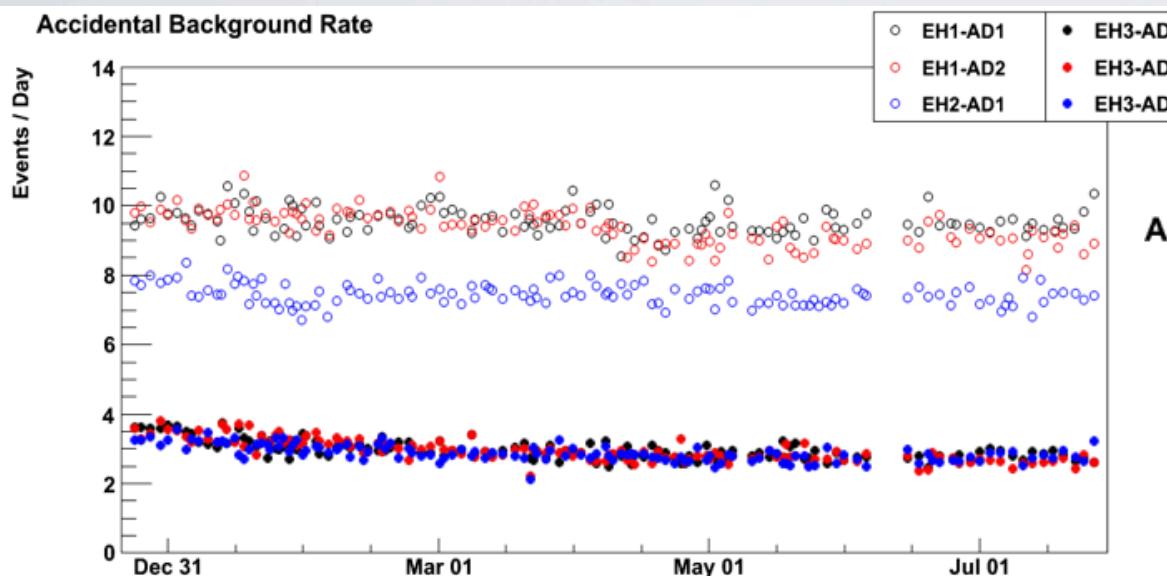


Capture time cut:
1 μs to 200 μs

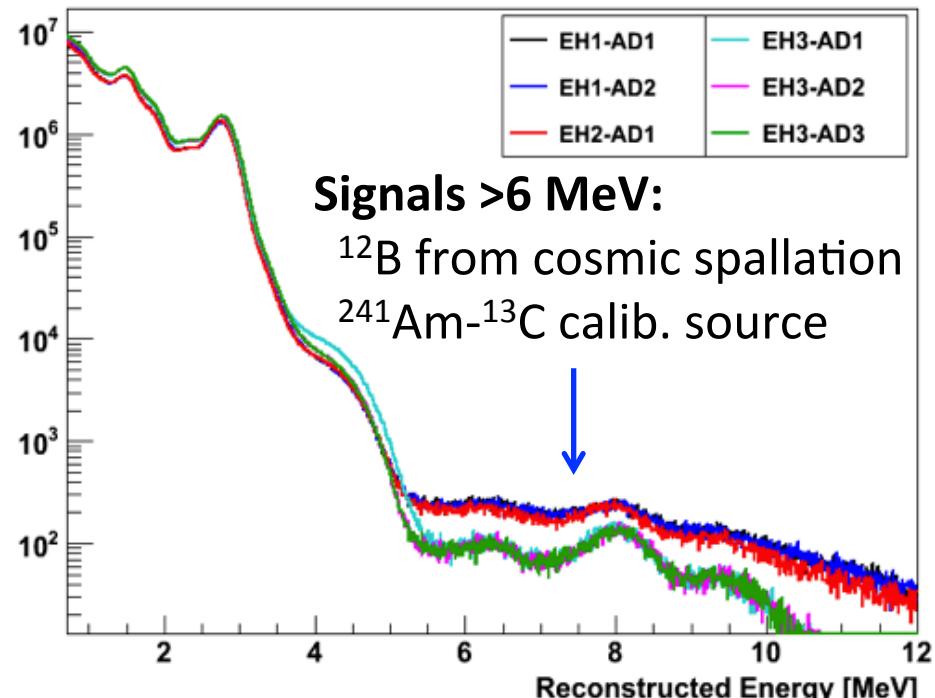
Efficiency uncertainty
within 0.01%
between detectors.

Accidental backgrounds

Two uncorrelated signals can accidentally mimic an antineutrino signal.



Accidental Spectrum



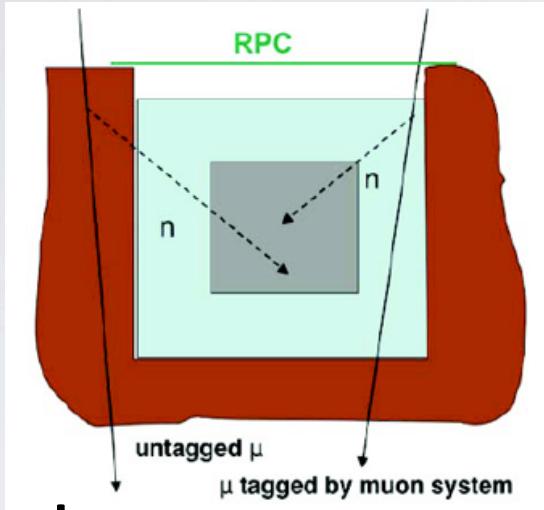
Accidental B/S is 4% (1.5%) of far (near) signal.

Accidental background be accurately modeled using uncorrelated signals in data.

→ Negligible uncertainty in background rate or spectra.

Signals >6 MeV:
 ^{12}B from cosmic spallation
 $^{241}\text{Am}-^{13}\text{C}$ calib. source

Fast-neutron backgrounds



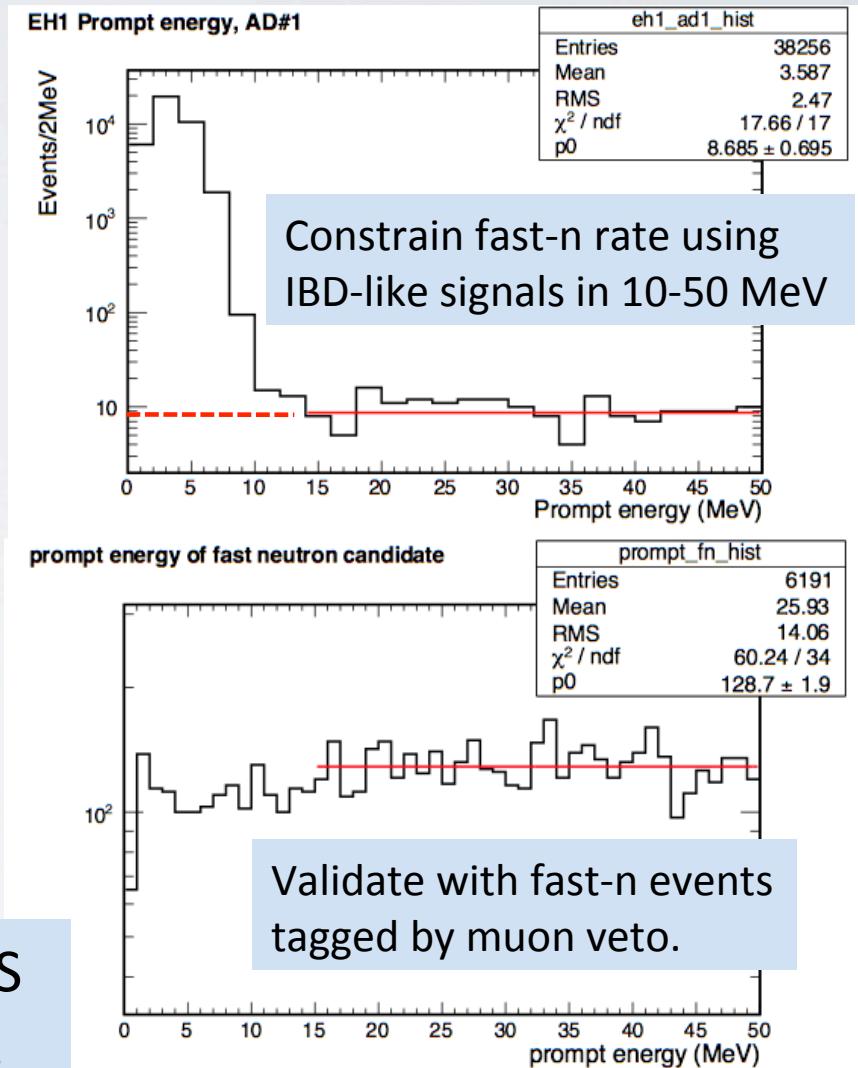
Fast Neutrons:

Energetic neutrons produced by cosmic rays
(inside and outside of muon veto system)

Mimics antineutrino (IBD) signal:

- Prompt: Neutron collides/stops in target
- Delayed: Neutron captures on Gd

Analysis muon veto cuts control B/S
to 0.06% (0.1%) of far (near) signal.



Reactor Flux Models

Antineutrino flux $S(E)$ from each reactor used to predict IBDs at each detector

	^{235}U	^{238}U	^{239}Pu	^{241}Pu
AD 1	63.3	12.2	19.5	4.8
AD 2	63.3	12.2	19.5	4.8
AD 3	61.0	12.5	21.5	4.9
AD 4	61.5	12.4	21.1	4.9
AD 5	61.5	12.4	21.1	4.9
AD 6	61.5	12.4	21.1	4.9

Approximate percentage of IBDs from each fission isotope at each detector

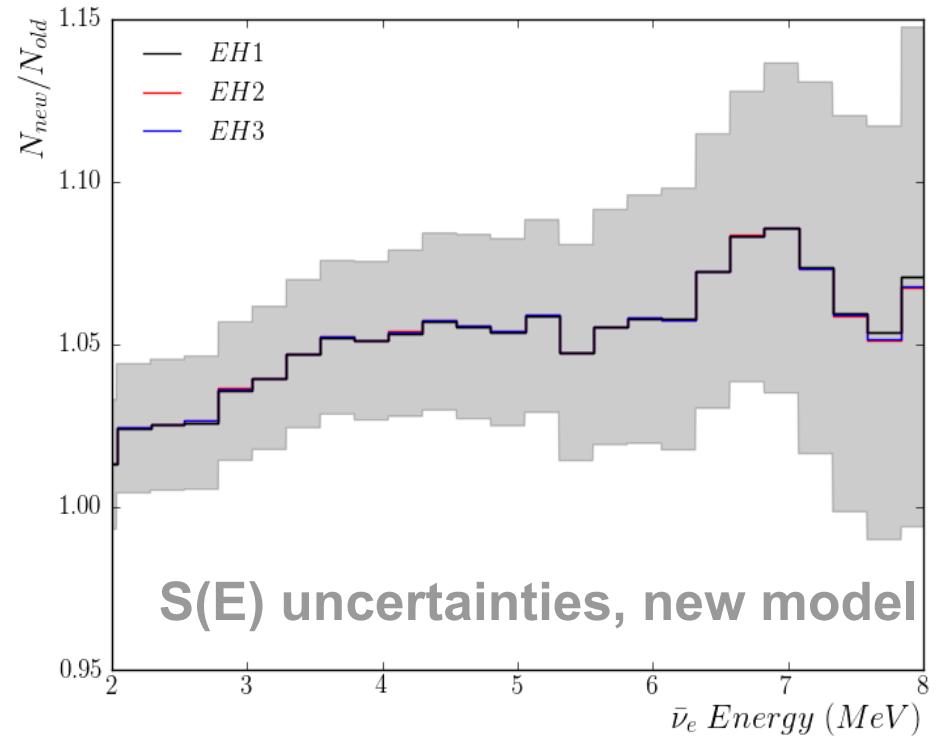
New model:

P. Huber, Phys. Rev. C84, 024617 (2011),
T. Mueller et al., Phys. Rev. C83, 054615 (2011)

Old model:

K. Schreckenbach et al., Phys. Lett. B160, 325 (1985)
A. A. Hahn et al., Phys Rev Lett. B218, 365 (1989)
P. Vogel et al. Phys. Rev. C24, 1543 (1981)

New/Old flux model difference in
unoscillated IBD prediction by hall



Flux model has negligible impact on
far vs. near oscillation measurement

Rate Uncertainty Summary

	Detector	
	Efficiency	Correlated
Target Protons		0.47%
Flasher cut	99.98%	0.01%
Delayed energy cut	90.9%	0.6%
Prompt energy cut	99.88%	0.10%
Multiplicity cut		0.02%
Capture time cut	98.6%	0.12%
Gd capture ratio	83.8%	0.8%
Spill-in	105.0%	1.5%
Livetime	100.0%	0.002%
Combined	78.8%	1.9%

With near/far measurement, correlated uncertainties cancel.

Only uncorrelated uncertainties are used.

Largest systematics are smaller than far site statistics (~1%)

	Reactor	
	Correlated	Uncorrelated
Energy/fission	0.2%	Power 0.5%
$\bar{\nu}_e$ /fission	3%	Fission fraction 0.6%
		Spent fuel 0.3%
Combined	3%	Combined 0.8%

Uncorrelated reactor systematics reduced by far vs. near measurement.

Daya Bay Future

Improved precision on oscillation parameters

- Constrains non-standard oscillation models
- Improves reach of future neutrino experiments

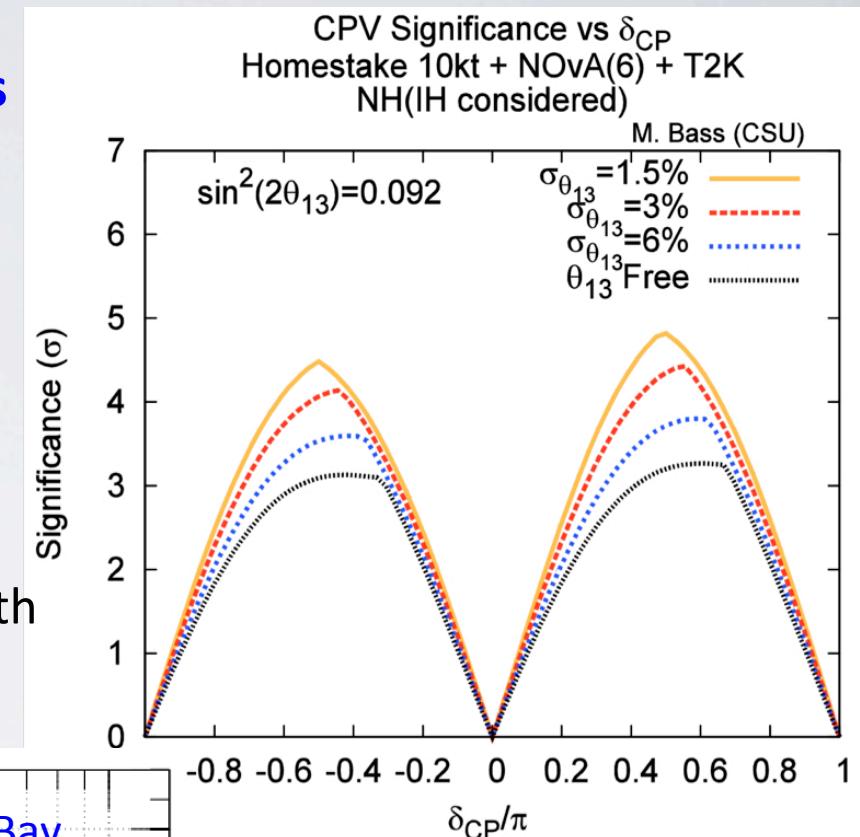
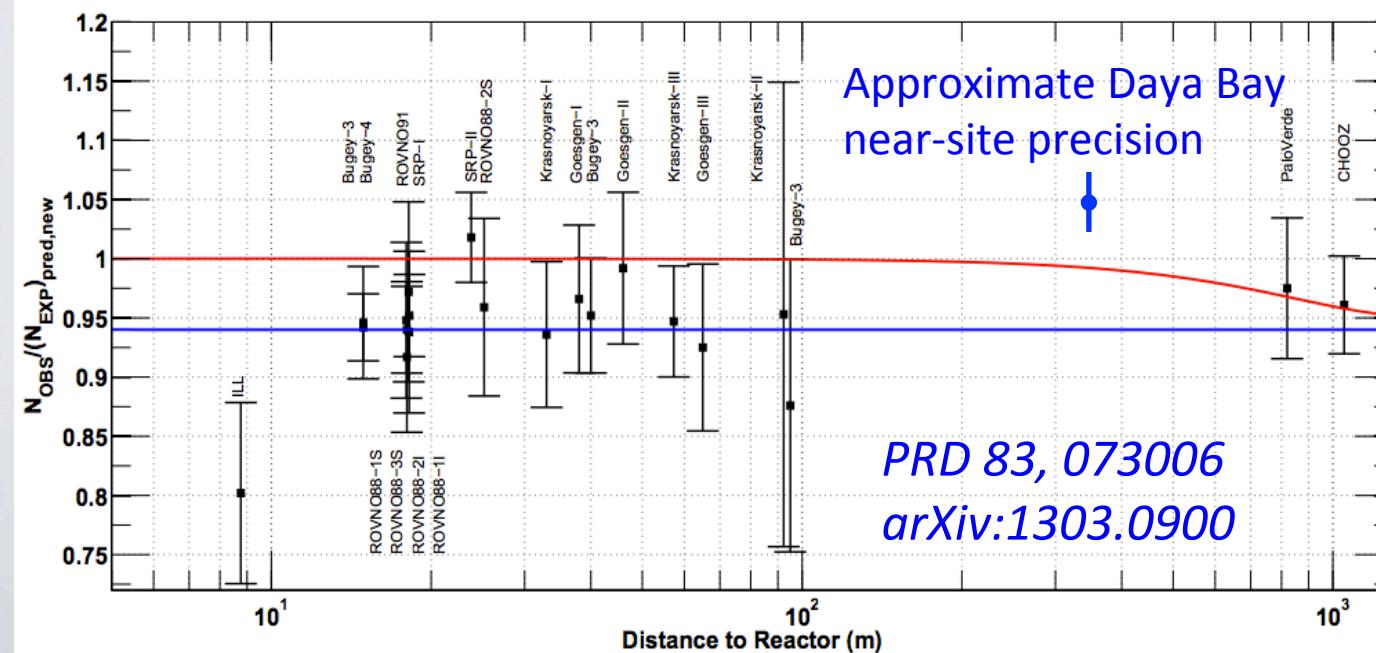
Measure absolute reactor neutrino flux

- Explore the ‘reactor antineutrino anomaly’
- Precise spectrum probes reactor models

Cosmogenic Backgrounds

- Measurement of cosmogenic production vs. depth

Supernova Neutrinos



χ^2 definition

$$\chi^2 = \sum_i^{det \times E_p} [N_i^{pred}(\theta_{13}, \Delta m_{ee}^2, \vec{f}, \vec{\eta}, \vec{\epsilon}, \vec{b}), -N_i^{data} + N_i^{data} \log \frac{N_i^{data}}{N_i^{pred}(\theta_{13}, \Delta m_{ee}^2, \vec{f}, \vec{\eta}, \vec{\epsilon}, \vec{b})}]$$

Reactor Flux Model Constraint

$$+ \sum_j^{site \times E_p} \sum_k^{site \times E_p} f_j V_{jk}^{-1} f_k$$

Energy Model Constraint

$$+ \sum_l^{abs.E} \frac{\eta_l^2}{\sigma_l^2}$$

Detector Efficiency Constraint

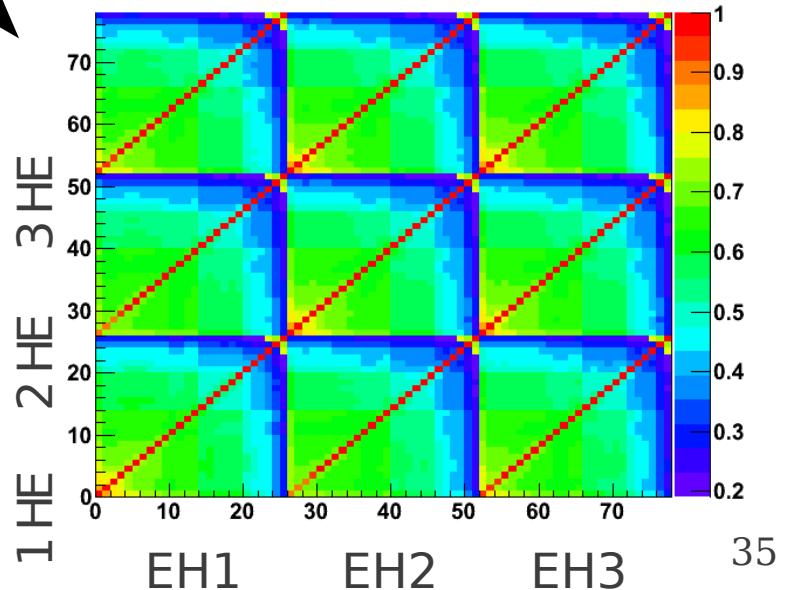
$$+ \sum_m^{det \times eff} \frac{\epsilon_m^2}{\sigma_m^2}$$

Background Constraint

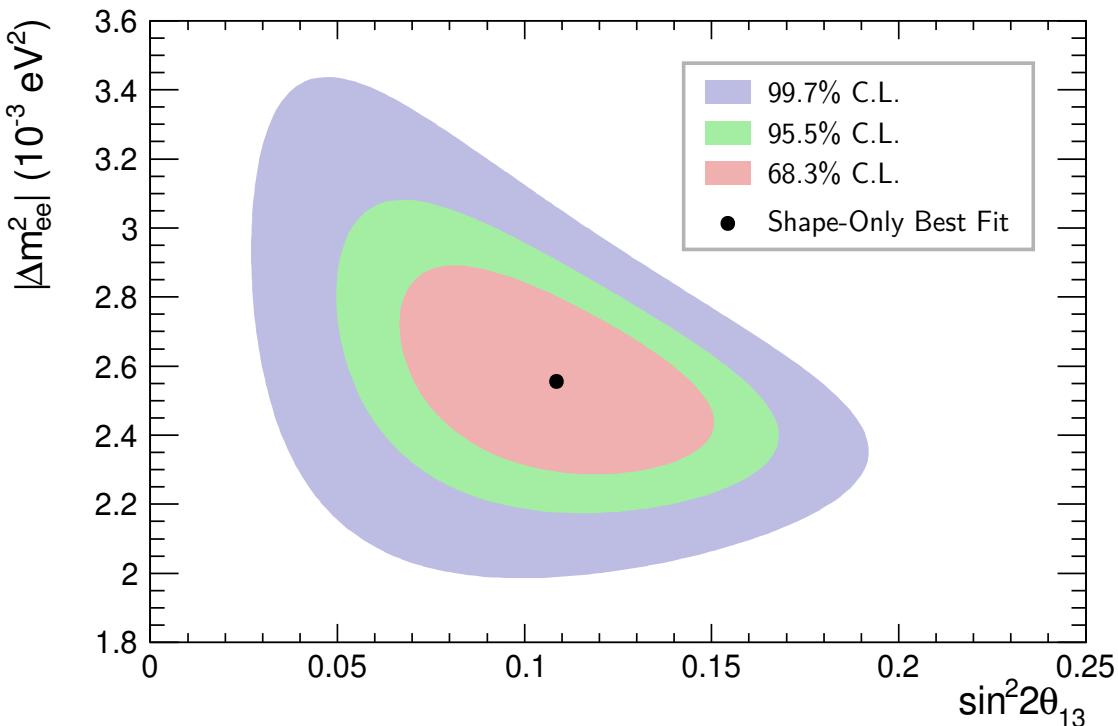
$$+ \sum_n^{det \times bg} \frac{b_n^2}{\sigma_n^2}$$

- Binned maximum likelihood method
- Constrain with the uncertainty from reactor flux model, background and relative detection efficiency.
 - Using covariance matrix to reduce number of the nuisance parameters for the reactor flux model.

Far vs. near relative measurement [No constraint on the absolute rate]



Pure Spectral Analysis



$$\sin^2 2\theta_{13} = 0.108 \pm 0.028$$

$$|\Delta m_{ee}^2| = 2.55^{+0.21}_{-0.18} \cdot 10^{-3} \text{ eV}^2$$

$$\chi^2/N_{\text{DoF}} = 161.2/148$$

$\theta_{13} = 0$ can be excluded at $> 3\sigma$ from spectral information alone

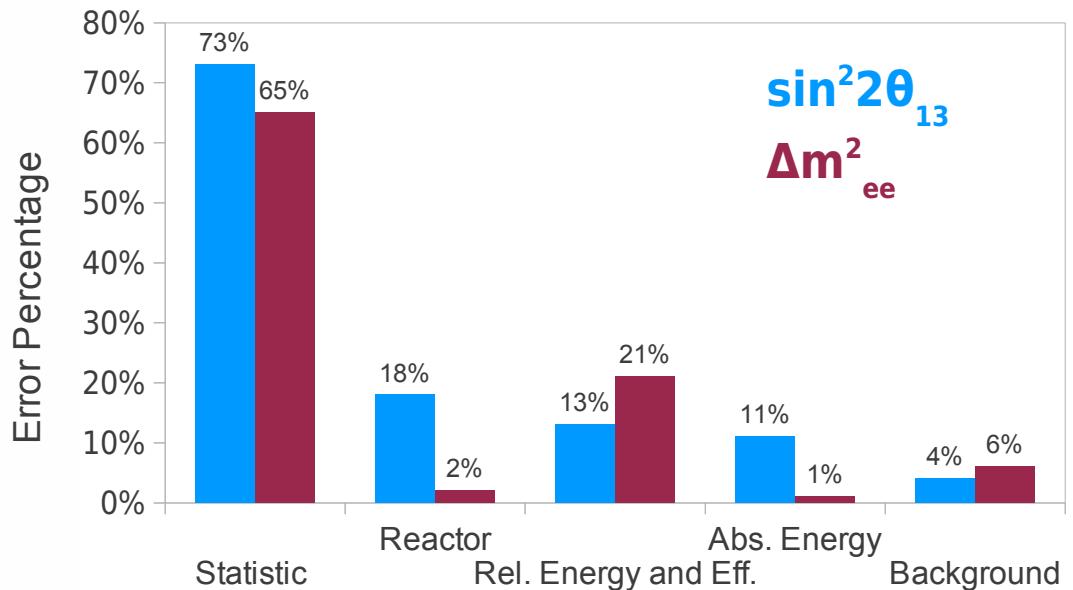
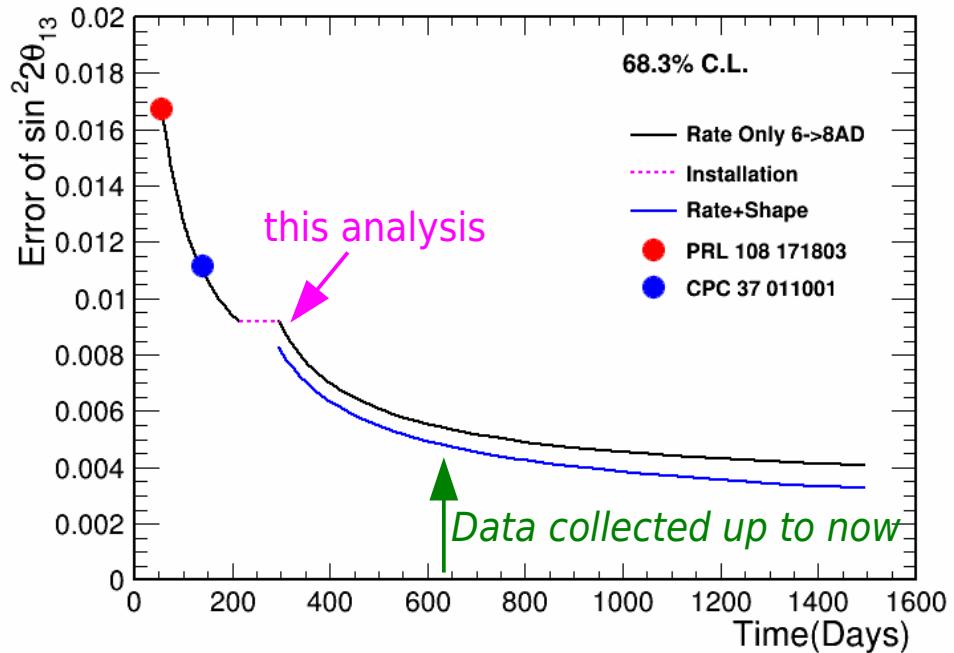
- For each AD, total event prediction fixed to observed data:

[1] θ_{13} free-floating: $\chi^2/N_{\text{DoF}} = 161.2/148$

[2] $\theta_{13} = 0$: $\chi^2/N_{\text{DoF}} = 178.5/146$

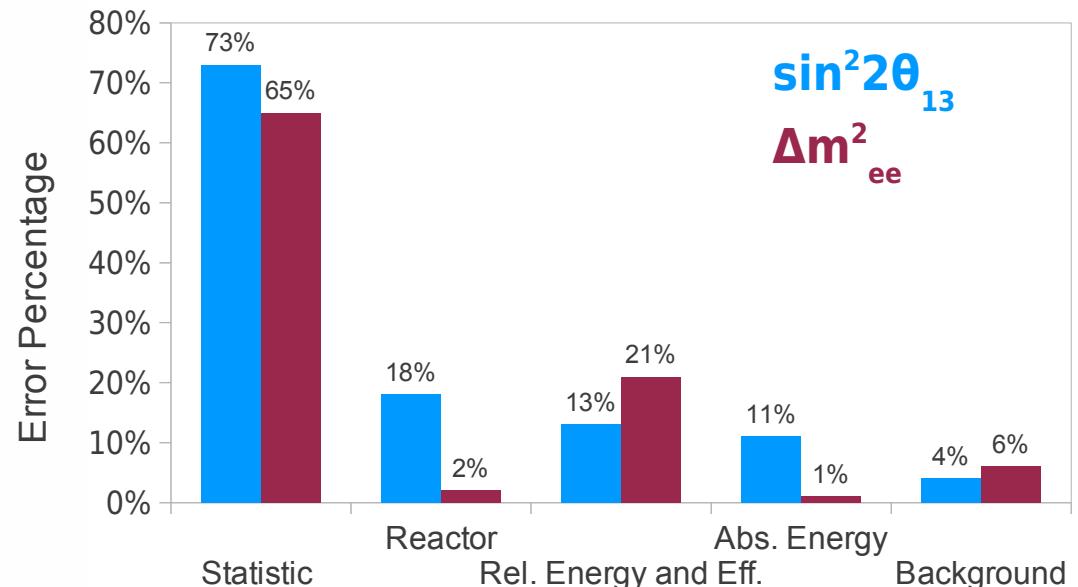
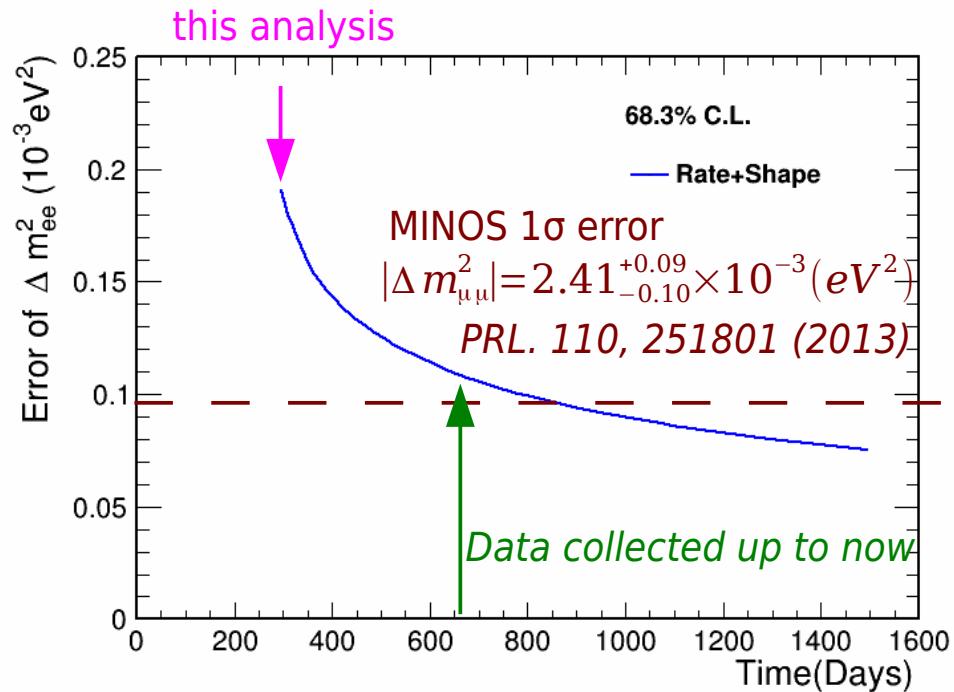
$$\Rightarrow \Delta\chi^2/N_{\text{DoF}} = 17.3/2, \text{ corresponding to } p = 1.75 \cdot 10^{-4}$$

$\sin^2 2\theta_{13}$ sensitivity projection



- Current errors are dominated by the statistical uncertainties (73%)
- Major systematics:
 - Reactor Model, relative+absolute energy and detector efficiency
- Daya Bay $\sin^2 2\theta_{13}$ final precision $\sim 4\%$, it can be further improved by adding nH capture analysis

Δm^2 sensitivity projection



- Current errors are dominated by the statistical uncertainties (73%)
- Major systematics:
 - Relative energy and background
- Daya Bay $|\Delta m^2_{ee}|$ final precision $\sim 0.1 \times 10^{-3} \text{ eV}^2$, comparable to the results from μ flavor sector

Making a Far Site prediction from the Near Site data

From the

- relative reactor core power info
- experimental layout geometry

it is possible to determine what fraction of events in each near detector at each true energy bin originate from each core.

Each of these components is then individually extrapolated to the far site

All reactor and detector correlated systematics, including the absolute flux and shape uncertainties, **cancel to first order**.

